NASA CR-134857
REPORT MDC J4526

DC-9 FLIGHT DEMONSTRATION PROGRAM WITH REFANNED JT8D ENGINES

FINAL REPORT

VOLUME I

SUMMARY

by

Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California 90846

Prepared for
National Aeronautics and Space Administration
NASA Lewis Research Center
Contract NAS 3-17841
Robert W. Schroeder, Project Manager

1. Report No. NASA CR-134857	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DC-9 FLIGHT DEMONSTRATION PROGRAM WITH REFANNED JT8D ENGINES, FINAL REPORT, VOLUME I, SUMMARY		5. Report Date July 1975
		6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No. MDC J4526
		10. Work Unit No.
9. Performing Organization Name and Address Douglas Aircraft Company McDonnell Douglas Corporation Long Beach, California		11. Contract or Grant No. NAS 3-17841
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes Project Manager, Robert W. Schroeder NASA Lewis Research Center Cleveland, Ohio		

16. Abstract

During the period of June 1973 to July 1975, Phase II of the NASA Refan Program, consisting of design, analysis, fabrication, and ground and flight testing of DC-9 Refan airframe/nacelle hardware with prototype JT8D-109 engines, was conducted.

The installation of the JT8D-109 engine on the DC-9 Refan airplane required new or modified hardware for the pylon, nacelle, and fuselage. The acoustic material used in the nose cowl was bonded aluminum honeycomb sandwich and the exhaust duct acoustic material was Inconel 625 Stresskin.

The sea level static, standard day bare engine takeoff thrust for the production JT8D-109 is 73 840 N (16,600 lb); relative to the JT8D-9 engine the takeoff thrust is 14.5 percent higher, the cruise TSFC at 9 144 m (30,000 ft), M = 0.80 and 19 571 N (4,400 lb) thrust is 1.5 percent lower, and the maximum cruise thrust available at the same Mach number and altitude is 4 percent higher. The range change of the DC-9 Refan relative to the production DC-9 airplane for long range cruise at 10 668 m (35,000 ft) and payloads in illustrating takeoff-gross-weight and fuel capacity limited cases are -352 km (-190 n.mi.) and -54 km (-29 n.mi.) respectively. Also, the range changes for 0.78 Mach number cruise at 9 144 m (30,000 ft) and payloads same as above are -326 km (-176 n.mi.) and -50 km (-27 n.mi.) respectively. The Refan airplane with the typical mission payload 6 804 kg (15,000 lb) and 694 km (375 n.mi.) range, shows less than 1 percent increase in block fuel for both long range and 0.78 Mach number cruise. The Refan airplane demonstrated flight characteristics similar to the production DC-9-30 and satisfied production airplane airworthiness requirements.

The noise levels determined from the DC-9 Refan flyover noise tests conducted in compliance with Federal Aviation Regulations, Part 36 were 95.3 EPNdB for sideline, 96.2 EPNdB for takeoff, 87.5 EPNdB for takeoff with cutback, and 97.4 EPNdB for landing approach. Additional flyover-noise tests of a production DC-9 C-9A airplane, flown alternately with the DC-9 Refan, resulted in noise levels for the C-9A of 95.7 EPNdB for takeoff with cutback and 106.1 EPNdB for landing approach.

Estimated unit cost of a DC-9 Refan retrofit program is 1.338 million in mid-1975 dollars with about an equal split in cost between airframe and engine.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
McDonnell Douglas DC-9 Refan Airplane, JT8D-109 Turbofan Engine, Acoustically Treated Nacelles, Flyover Noise, Community Noise Contours, DC-9 Series 30 C-9A Airplane Noise Levels.	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	74	

* For sale by the National Technical Information Service, Springfield, Virginia 22151

TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	3
AIRPLANE DESCRIPTION	5
DESIGN AND CONSTRUCTION	9
Pylon	11
Fuselage Modifications	13
Engine Mount System	15
Nacelle	17
Engine and Nacelle Subsystem Development	23
Fire Protection	29
PERFORMANCE AND ANALYSIS	31
Engine Performance	33
Airplane Performance	37
Airplane Stability and Control	45
Airplane/Prototype Engine Performance	47
Airplane Structural Integrity and Dynamics	53
FLYOVER NOISE	55
Noise Levels at FAR Part 36 Locations	57
Airport Community Noise	59
RETROFIT AND ECONOMICS ANALYSIS	61
SUMMARY OF RESULTS AND CONCLUSIONS	63
REFERENCES	65
SYMBOLS	67

SUMMARY

The purpose of the DC-9 Refan Program was to establish the technical and economic feasibility of reducing the noise of existing JT8D powered DC-9 aircraft. The Refan Program was divided into two phases.

Phase I provided engine and nacelle/airplane integration definition documents for installation of the JT8D-109 engine on the DC-9 series airplane, prepared preliminary design of nacelle and airplane modifications, conducted model tests for design information, and prepared analyses for economic and retrofit considerations. Phase II included detail analyses, hardware design and fabrication, and flight testing to substantiate the design and obtain flyover noise data.

The JT8D-109 engine, a derivative of the basic Pratt and Whitney JT8D-9 turbofan engine with the minimum treatment acoustic nacelle was selected in Phase I for the design, analysis, construction, and the flight demonstration program of Phase II.

This report summarizes the design and construction, performance and analysis, and flyover noise test results for the DC-9 Refan flight demonstration airplane carried out under Phase II, Contract NAS 3-17841.

The installation of the JT8D-109 engine on the DC-9 Refan airplane required new or modified hardware for the pylon, nacelle, and fuselage. The JT8D-109 engine and nacelle subsystem arrangement was identical to the production DC-9 systems.

The acoustic material used in the nose cowl was bonded aluminum honeycomb sandwich and the exhaust duct acoustic material was Inconel 625 Stresskin.

The sea level static, standard day bare engine takeoff thrust for the production JT8D-109 is 73 840 N (16,600 lb); relative to the JT8D-9 engine the takeoff thrust is 14.5 percent higher, the cruise TSFC at 9 144 m (30,000 ft), M = 0.80 and 19 571 N (4,400 lb) thrust is 1.5 percent lower, and the maximum cruise thrust available at the same Mach number and altitude is 4 percent higher.

The installation of the JT8D-109 engine results in an operational weight increase of 1 041 kg (2,294 lb) and an aft operational empty weight center of gravity shift of 6 to 7 percent M.A.C. At sea level standard day conditions the additional thrust of the JT8D-109 results in 2 040 kg (4,500 lb) additional takeoff gross weight capability for a given field length.

The range change of the DC-9 Refan relative to the production DC-9 airplane for long range cruise at 10 668 m (35,000 ft) and payloads illustrating takeoff-gross-weight and fuel capacity limited cases are -352 km (-190 n.mi.) and -54 km (-29 n.mi.) respectively. Also, the range changes for 0.78 Mach number cruise at 9 144 m (30,000 ft) and payloads same as above are -326 km (-176 n.mi.) and -50 km (-27 n.mi.) respectively.

The DC-9 Refan airplane with the typical mission payload 6 804 kg (15,000 lb) and 694 km (375 n.mi.) range, shows less than 1 percent increase in block fuel for both the long range cruise at 10 668 m (35,000 ft) and 0.78 Mach number cruise at 9 144 m (30,000 ft) cases.

Final airplane performance analysis was completed after the engine manufacturer evaluated Ground Static and NASA Lewis Altitude Test data and updated the production JT8D-109 engine computer deck.

The Refan airplane demonstrated stall, static longitudinal stability, longitudinal control, longitudinal trim, air and ground minimum control speeds, and directional control characteristics similar to the production DC-9-30 and satisfied production airplane airworthiness requirements.

The DC-9 Refan airplane structural and dynamic analytical results compared to ground and flight test data substantiate program requirements that the nacelle, thrust reverser, hardware, and the airplane structural modifications are flightworthy and certifiable and that the Refan airplane meet flutter speed margins.

The noise levels determined from the DC-9 Refan flyover noise tests conducted in compliance with Federal Aviation Regulations, Part 36 were 95.3 EPNdB for sideline, 96.2 EPNdB for takeoff, 87.5 EPNdB for takeoff with cutback, and 97.4 EPNdB for landing approach. Additional flyover-noise tests of a production DC-9 C-9A airplane, flown alternately with the DC-9 Refan, resulted in noise levels for the C-9A of 95.7 EPNdB for takeoff with cutback and 106.1 EPNdB for landing approach.

Estimated unit cost of a DC-9 Refan retrofit program is 1.338 million in mid-1975 dollars with about an equal split in cost between airframe and engine.

Installation and testing of the prototype flight test JT8D-109 engines was accomplished within the scope of normal procedures with no unusual problems. The engine operations were excellent and engine performance was very close to the predicted levels.

INTRODUCTION

The continuing growth of the air transportation industry with resulting increased numbers of operations from established or emerging airports coupled with increased population density near airports, has resulted in an effort to control human exposure to airplane noise. The government and industrial organizations have therefore aggresively supported programs directed at producing airplane and engine designs offering meaningful reductions in airport community noise.

During the late 1960's research related to the noise within the engine itself and research related to absorptive materials were sufficiently refined to have been applied to the development of the quieter high bypass ratio turbofan power plants for the new generation of wide-body commercial transports.

However, a large portion of the existing and expanding fleet of standard bodied transports are powered by the JT3D or JT8D low bypass ratio engines. Since early retirement of these airplanes or re-engining with a totally new high-bypass ratio engine are not competitive in terms of timeliness or economics, two approaches to solve the noise problem of these low bypass ratio engines appear to be feasible.

One approach would be to apply the technology of sound absorbing materials (SAM) to nacelle treatment with possibly a jet noise suppressor. A number of government and industry studies have considered this approach (SAM) and standard body transports being delivered in the mid-1970's include this technology.

A second approach would be to incorporate the technology of the high-bypass ratio engines into the JT3D and JT8D family. This would require replacement of the present low bypass ratio engine fans with larger fans while maintaining the hardware and general operating characteristics of the core engine. This would result in a substantial reduction in jet exhaust noise, of particular interest for the JT8D engine, with the possibility of improved engine fuel consumption and a substantial improvement in thrust.

In August 1972, the NASA Lewis Research Center authorized the Douglas Aircraft Company, The Boeing Company, and Pratt and Whitney Aircraft to develop and establish the economic and technical feasibility of reducing noise by developing engine and airframe/nacelle modifications. The program covered the JT3D engine and the DC-8 and B-707 it powers and the JT8D engine and the DC-9, B-727 and B-737 it powers. At the end of approximately four and one-half months all effort on the JT3D was terminated. All subsequent studies were performed on a derivative of the Pratt and Whitney JT8D-9 engine designated the JT8D-109. The Douglas Aircraft Company Phase I effort is summarized in reference 1.

On the basis of the results of the Phase I effort the Douglas Aircraft Company was authorized on 30 June 1973 to proceed with a Phase II study that would include the nacelle/airplane design and construction, kit costs, ground compatibility tests, flight worthiness, flight engine/airplane performance and flyover noise tests. The Douglas Aircraft Company Phase II effort is reported under three principal areas; Design and Construction, Performance and Analysis, and Flyover Noise.

This volume (Volume I) of the NASA Refan Program Phase II final report contains a summary of the Design and Construction, Performance and Analysis, and Flyover Noise test results for the DC-9 Refan flight demonstration airplane.

The design effort that established the flight demonstration configuration for the nacelle, pylon, thrust reverser, subsystems, and fuselage including hardware construction is reported in Volume II, reference 2.

Volume III (reference 3) contains the following:

1) A comparison of the performance and physical characteristics of the production JT8D-109 and JT8D-9 engines.

2) A comparison of the performance of the production DC-9-30 and the DC-9 Refan airplane with production JT8D-9 and JT8D-109 engines installed, respectively.

3) An evaluation of the stability and control characteristics of the DC-9 Refan airplane.

4) An evaluation of the DC-9 Refan airplane/engine performance with the two prototype JT8D-109 flight test engines installed.

5) A summary of the structural and dynamic analysis.

6) An evaluation of the results from ground tests that were conducted prior to flight testing and an evaluation and comparison of flight test data with analytical results.

7) An evaluation of the results from the structural and aerodynamic damping flight tests.

8) A summary of the retrofit and economic analysis.

FAR Part 36 noise levels, EPNL and dB(A) - distance maps, noise contours, spectral studies on extra ground attenuation, turbulence, ground reflection, noise source levels, static-to-flight predictions, and the engine/nacelle acoustical characteristics of the DC-9 Refan airplane are reported in Volume IV, reference 4.

This report contains both U.S. Customary and International System (SI) Units; however, all calculations and measurements were made using the U.S. Customary Units.

AIRPLANE DESCRIPTION

The DC-9 airplane is a low wing, two-engine, T-tail, short-to-medium range, commercial transport produced in five basic Series (10, 20, 30, 40 and 50 plus derivatives of those series). The engines are located at the rear of the airplane and mounted on pylons attached to the left and right side of the fuselage. Production models of the DC-9 are the -14/15, -15F, -20, -31, 32, -32F, 40, -50, the Air Force C-9A and the Navy C-9B. These models vary widely in takeoff gross weights, fuel tank arrangement, fuselage length, wing area and JT8D engine model (figure 1).

Figure 1 shows a simplified genealogy of the DC-9 family starting from the first model (Series 10) and showing the important changes made from model to model through the latest "stretched" versions. The most significant change in the DC-9 model was introduced with the initiation of the DC-9-30 Series. At that time, the fuselage was lengthened approximately 4.55 m (179 in.), the wing span was increased 1.22 m (48 in.) and full span leading edge slats were incorporated.

A production model DC-9-31 with a structurally modified fuselage, a new shorter span pylon, a new larger long duct nacelle and thrust reverser with the JT8D-109 engine installed was used for the DC-9 Refan flight demonstration (figure 2). The Refan airplane was operated at takeoff gross weights up to 49 032 kg (108,000 lb), and landing gross weights of 44 946 kg (99,000 lb).

ORIGINAL PAGE IS OF POOR QUALITY

DC-9 SERIES 10
JT8D-7
MTOGW 77,000 TO 90,700 lb
(34 900 TO 41 100 kg)
SLOTTED FLAPS

↓

WING SPAN INCREASED 48 in. (1.22 m)
LEADING EDGE SLATS ADDED

↓

DC-9 SERIES 20
JT8D-9
MTOGW 98,000 lb
(44 500 kg)

↓

FUSELAGE EXTENDED 179 in. (4.55 m)
WING SPAN INCREASED 48 in. (1.22 m)
REVISED LANDING GEAR

↓

DC-9 SERIES 30 → DC-9-31, JT8D-7, -9 & -11, MTOGW 98,000 TO 100,000 lb (44 500 TO 45 400 kg) → DC-9-32, JT8D-7, -9, & -11, MTOGW 108,000 lb (49 000 kg) → WING INCIDENCE ANGLE INCREASED 1-1/4 deg (0.022 rad), WING STRENGTHENED, LANDING GEAR STRENGTHENED → DC-9-33, JT8D-9 & -11, MTOGW 114,000 lb (51 700 kg)

↓

WING INCIDENCE ANGLE INCREASED
1-1/4 deg (0.022 rad)
WING STRENGTHENED
LANDING GEAR STRENGTHENED
FUSELAGE EXTENDED 76 in. (1.93 m)

↓

DC-9 SERIES 40
JT8D-11
MTOGW 114,000 lb
(51 700 kg)

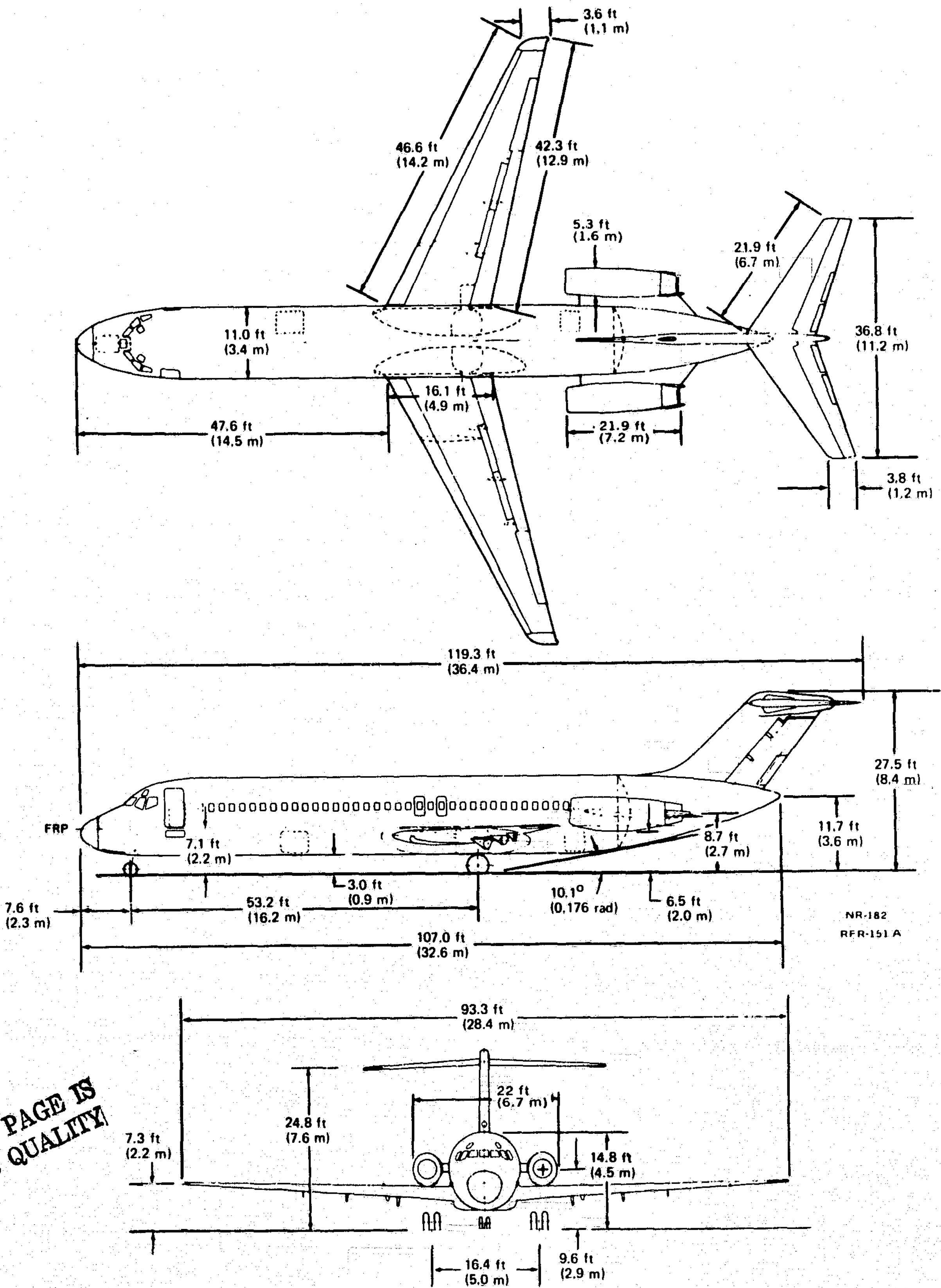
↓

FUSELAGE EXTENDED 95 in. (2.4 m)
WING STRENGTHENED
FUSELAGE STRAKES ADDED

↓

DC-9 SERIES 50
JT8D 15 AND 17
MTOGW 121,000 lb
(54 934 kg)

FIGURE 1. DC-9 GENEALOGY



ORIGINAL PAGE IS OF POOR QUALITY

FIGURE 2. DC-9 REFAN THREE-VIEW

DESIGN AND CONSTRUCTION

The installation of the JT8D-109 engine on the DC-9 Refan airplane required new or modified hardware for the pylon, nacelle, and fuselage.

During the early design and fabrication stages, highly experienced manufacturing personnel working directly with the design engineers were able to evaluate and propose cost saving ideas for direct incorporation into the hardware design for tool requirements, ease of manufacturing, and assembly and subsystem development.

Production was controlled by a manufacturing plan and schedule which sequenced fabrication, assembly, development, and the installation of Refan airplane hardware. Only low-cost mandatory tooling was used. Shop aids and one of a kind soft tools were used wherever possible. Figure 3 shows typical fabrication and assembly sequencing of a major component and typical soft tooling. The soft tooling was capable of producing one shipset of parts for the flight demonstration airplane and a limited number of parts for retrofit kits, each part suitable for certification under Federal Aviation Regulations.

Douglas Quality and Reliability Assurance personnel and the established inspection systems and procedures of the production DC-9 Program, which are in compliance with Federal Aviation Administration regulations, were used throughout the program for inspection and verification of all parts, assemblies and installations.

Refan modification to the airplane fuselage structure and all Refan hardware installations were found airworthy and qualified under Federal Aviation Administration regulations for an experimental flight ticket.

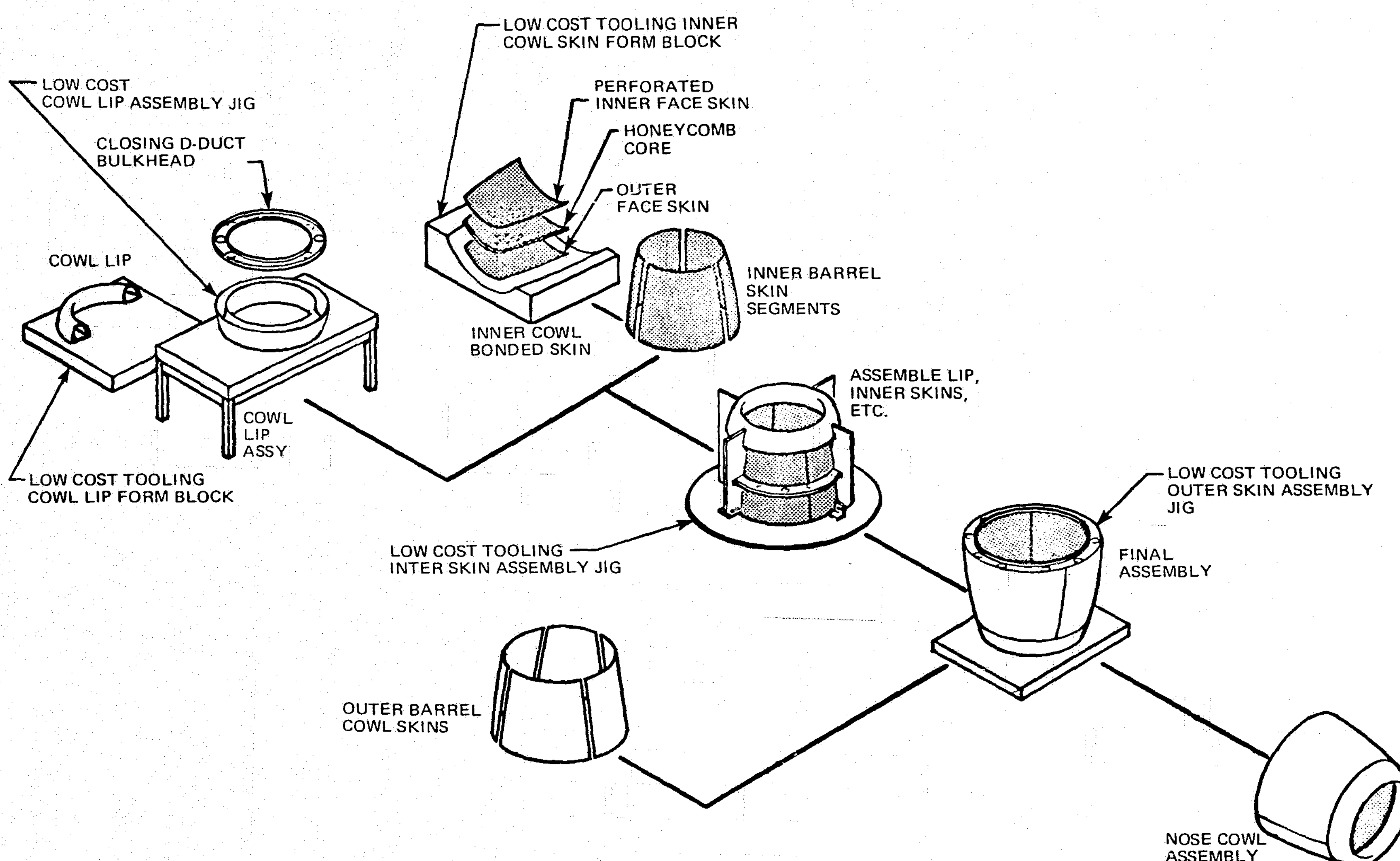


FIGURE 3. DC-9 REFAN NOSE COWL COMPONENTS FABRICATION AND ASSEMBLY – TYPICAL SEQUENCING AND LOW COST TOOLING

Pylon

Optimization of the pylon design for the JT8D-109 engine installation was accomplished during Phase I by conducting a pylon configuration trade study (ref. 1). The trade study evaluated the effects of varying pylon widths on high speed cruise drag, low speed stall recovery, minimum ground and air control speeds, and nacelle/pylon accessibility.

Wind tunnel tests were conducted in Phase I (references 5 and 6) to sort out the aerodynamic considerations. The test results indicated that the JT8D-109 engine nacelle could be installed on a pylon from 132 mm (5.2 in.) to 279.4 mm (11.0 in.) in width without detriment to airplane performance or stability characteristics.

Utilizing design layouts and a full scale pylon mockup, it was determined that in order to provide adequate accessibility through the pylon to the subsystem interface connections and adequate support structure for the access doors, the pylon would require the following characteristics:

- Outside nacelle contour 58.5 mm (2.3 in.) outboard of production nacelle contour.

- Engine centerline moved inboard 81.3 mm (3.2 in.) of production engine centerline.

- Pylon width at upper front spar 204.2 mm (8.05 in.).

Consequently, the DC-9 Refan airplane pylon was completely redesigned to reduce its width from 425.45 mm (16.75 in.) to 204.5 mm (8.05 in.) and to increase its load carrying capabilities to accommodate the heavier JT8D-109 engine and nacelle. The reduction in pylon width results from a combination of the engine centerline moving 81.3 mm (3.2 in.) closer to the fuselage and the increase in engine diameter of 279.4 mm (11 in.).

The new pylon is structurally similar to the production DC-9 pylon, with front and rear engine mount spars, a closing rib adjacent to the nacelle apron, a fully skinned upper surface, and access panels in the aft lower surface (figure 4). The production pylon secondary firewall (not an FAA requirement) is deleted, and a thicker titanium fuselage skin panel serves as the firewall for the JT8D-109 engine installation. In addition, the area adjacent to the engine burner cans has a columbium burn-through barrier attached approximately 10.1 mm, (0.4 in.) outboard of the fuselage skin.

The pylon leading and trailing edge fairings are constructed similarly to the production units; i.e., upper and lower skins, attach angles, a closing rib, and longitudinal formers.

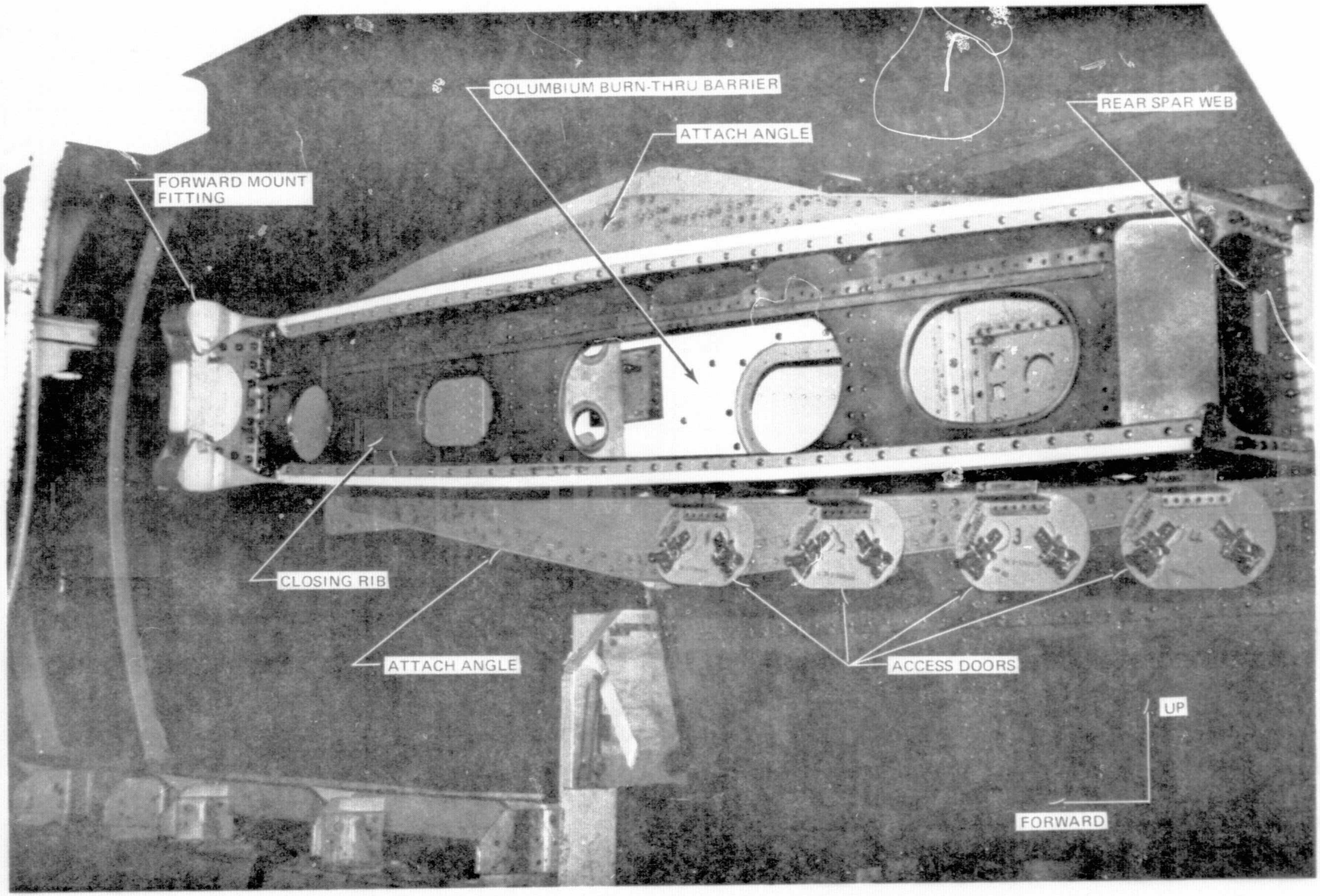


FIGURE 4. DC-9 REFAN PYLON BOX STRUCTURE

ORIGINAL PAGE IS
OF POOR QUALITY

Fuselage Modifications

In order to accept the higher static and dynamic loads imposed by the installation of the JT8D-109 engine, the production DC-9 Series 30 fuselage structure required modifications in the following areas:

- Replace the fuselage titanium skin panels adjacent to the pylon with a heavier gauge.
- Reinforce the front spar mount frame at Y = 965.091.
- Reinforce the two intermediate frames at Y = 980 and Y = 1019.
- Reinforce the rear spar mount frame at Y = 1038.868.
- Reinforce the fuselage keel in the main landing gear area.

The production titanium skin panels and doublers of 0.812 mm (0.032 in.) thickness from Y = 937 to Y = 996 between longerons 14 and the fuselage floor and from Y = 996 to Y = 1087 between longerons 14 and 18 were removed and replaced by panels 3.17 mm (0.125 in.) chem-milled to 2.03 mm (0.080 in.) and 1.27 mm (0.050 in.) in non-critical areas.

The front spar mount frame at Y = 965.091 was reinforced by removing the production aluminum web and doubler, from just above longeron 13 down to the fuselage floor, and replacing it with thicker components manufactured from titanium.

The two frames at Y = 980 and Y = 1019 were reinforced by means of cap stiffening strips and web doublers, in order that they could take the loads imposed on them by the upper and lower pylon attach fittings.

The rear spar mount frame at Y = 1038.868 was reinforced by removing the production aluminum web from longeron 14 to longeron 18, and replacing it with a heavier gauge.

The production keel is made of frames and ribs fitted to the inside of the door jamb members and skin. In order to make changes on a retrofit basis without substantial modification of production parts, nested straps and channels were added to the face of the door jamb members and an external doubler added on the surface of the lower skin.

Engine Mount System

The production JT8D engine mount system used on the DC-9 airplane is a three point system utilizing an upper and lower mount in the same station plane on the forward end of the engine and one mount on the engine horizontal centerline at the aft end.

The mount system for installation of the JT8D-109 engine on the DC-9 Refan airplane was the same as production, except that additional reinforcement was required at the forward mount (figure 5) to accept the higher loads and the upper attachment link for the aft engine mount (figure 6) was also redesigned.

The production type tuned vibration absorbers which are installed on the forward mount yoke (figure 5) were used on JT8D-109 prototype engine during the flight demonstration program; however, no attempt was made to quantitatively evaluate the cabin noise levels.

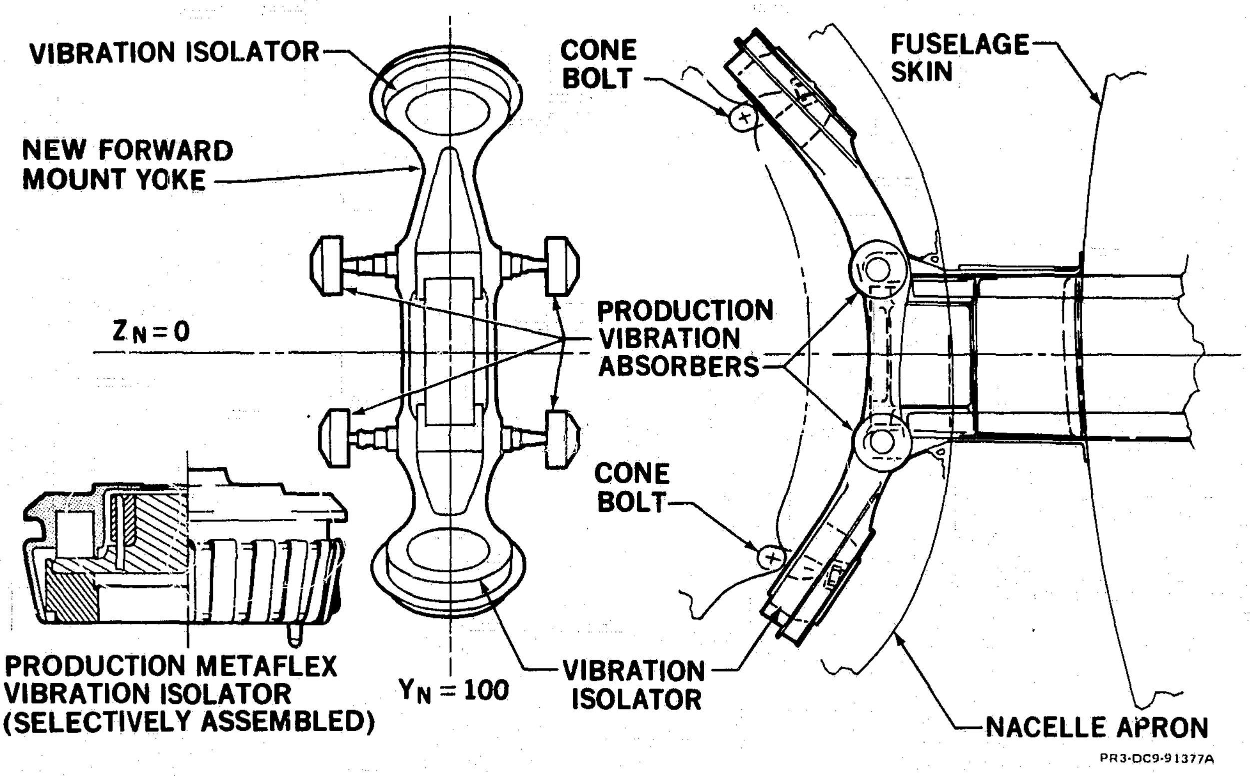


FIGURE 5. DC-9 REFAN JT8D-109 ENGINE FORWARD MOUNT VIBRATION ABSORBERS AND ISOLATORS

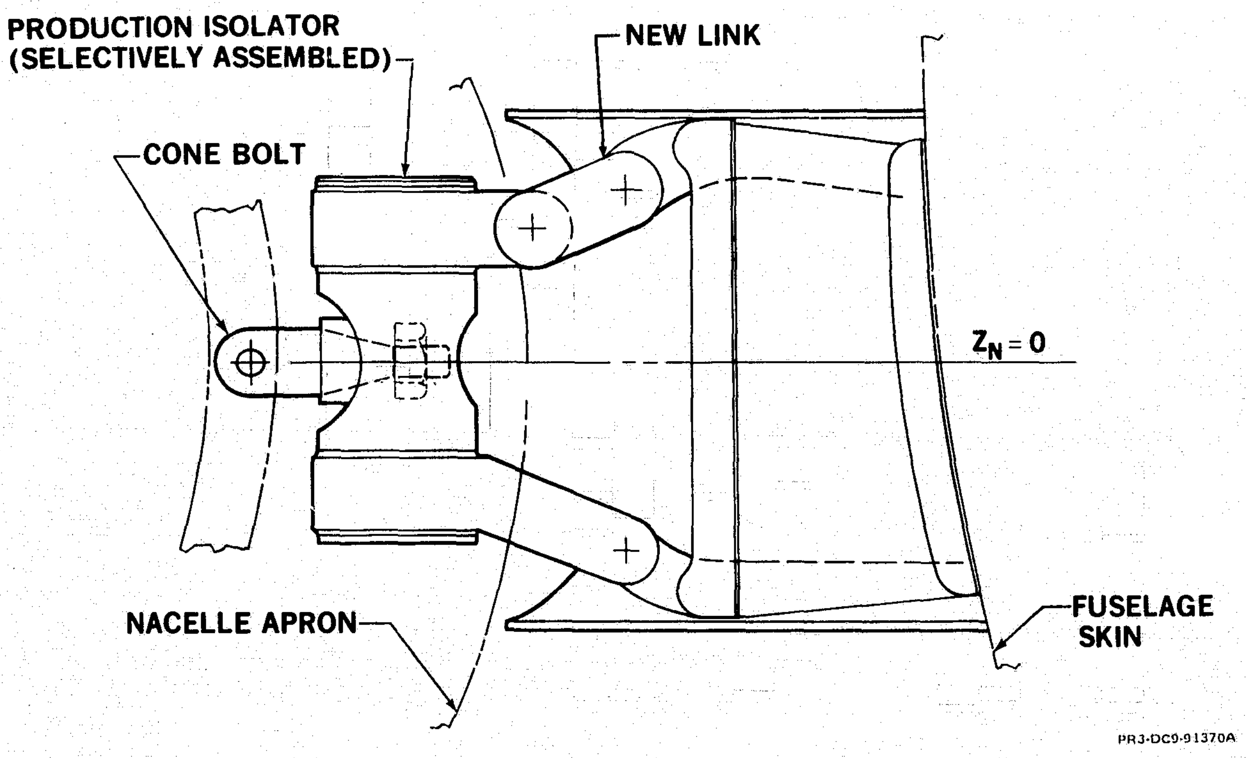


FIGURE 6. DC-9 REFAN JT8D-109 ENGINE AFT MOUNT AND VIBRATION ISOLATOR

Nacelle

New JT8D-109 engine nacelles were designed and fabricated to achieve the desired noise suppression goals and retain or improve the present production nacelle maintenance and access provisions for the engine and accessories.

The nacelle configuration incorporates acoustically treated material in the nose cowl and exhaust duct. The nacelle retains the production engine nacelle exhaust concept of mixing and discharging fan air with primary air and the single target-type reverser to reverse the fan and primary exhaust streams.

The JT8D-109 engine nacelle (figure 7) required a new nose cowl and bullet, new upper and lower access doors, new pylon aprons, and a new exhaust duct and thrust reverser

The nose cowl is symmetrical about the centerline and is interchangeable on either engine position. Using DC-10 inlet design technology the nose lip was designed with a larger thickness ratio than the production DC-9 inlet for additional operating margin in crosswinds without inlet boundary layer separation. The inlet was also sized for relatively low throat Mach numbers to allow for possible engine airflow growth.

The nose cowl (figure 8) consists of an inner barrel fabricated from a bonded aluminum honeycomb sandwich surrounded by an outer skin supported by circumferential stiffeners. The barrel functions as the principal load carrying component. At the aft end of the barrel is the nose cowl attach ring which transfers the loads into the engine fan case. A double wall leading edge lip and closing bulkhead are attached to the forward end of the barrel forming a D-duct. The leading edge is anti-iced by ducting engine bleed air into the D-duct. An aft bulkhead, fabricated from titanium for fire protection, closes the nose cowl inner and outer skins and forms the land for the forward edge of the nacelle access doors. The nose cowl is attached to the engine inlet flange by using 24, 7.938 mm (0.312 in.) diameter bolts and 2 index pins.

The acoustic treatment (figure 9) consists of three separate circumferential panels of the inner barrel with the perforated face sheets on the inner flow path.

The access doors and pylon apron are identical in the design concept and method of construction to the production DC-9 articles.

The access doors consists of five hinge/latch frames, leading and trailing edge closing frames and upper and lower longerons and uses production DC-9 latches.

The apron is the structure that forms the aerodynamic interface between the nacelle and pylon. The apron consists of five hinge/hook frames and is fabricated in the same manner as the access doors.

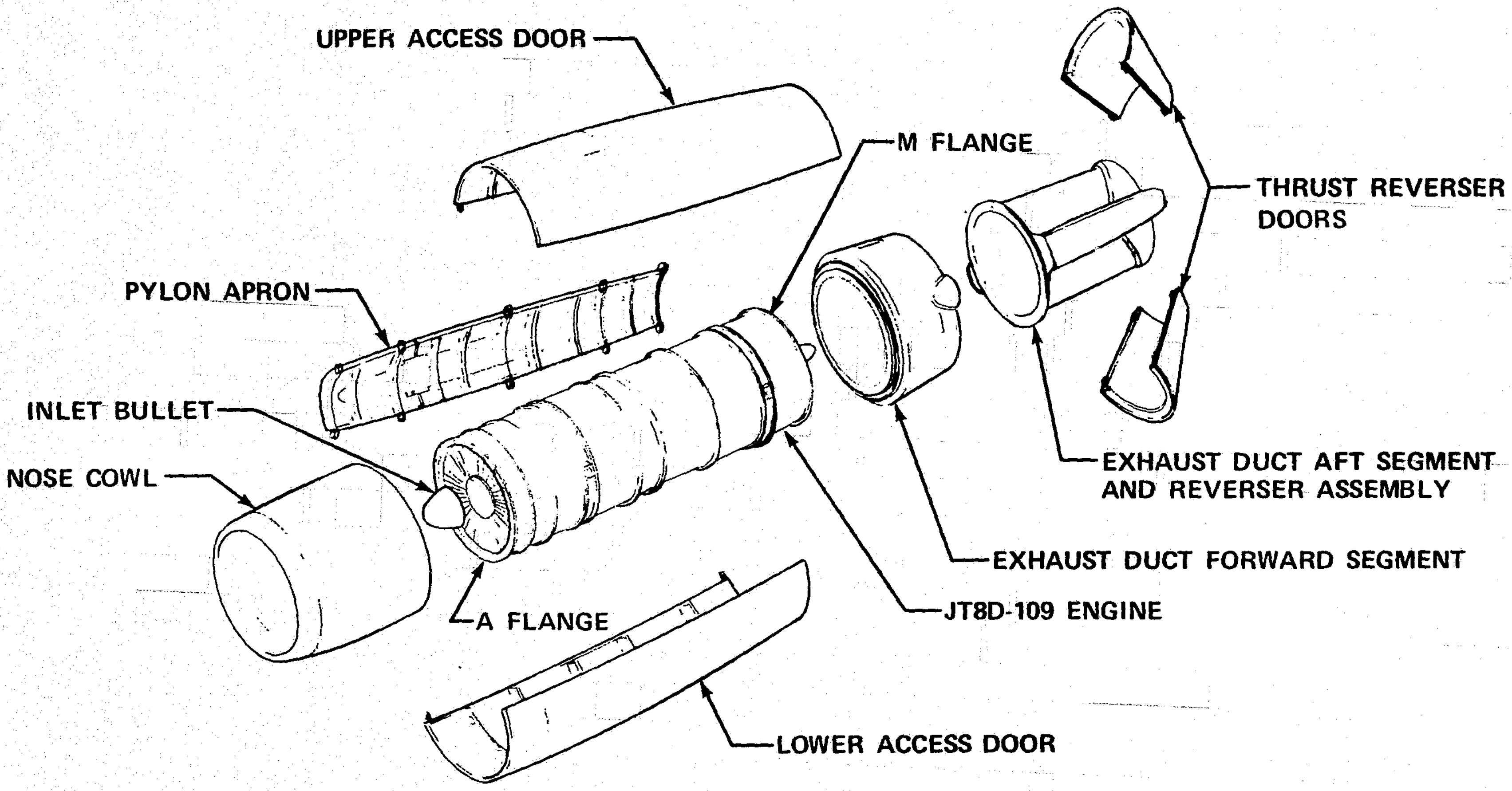


FIGURE 7. DC-9 REFAN NACELLE HARDWARE

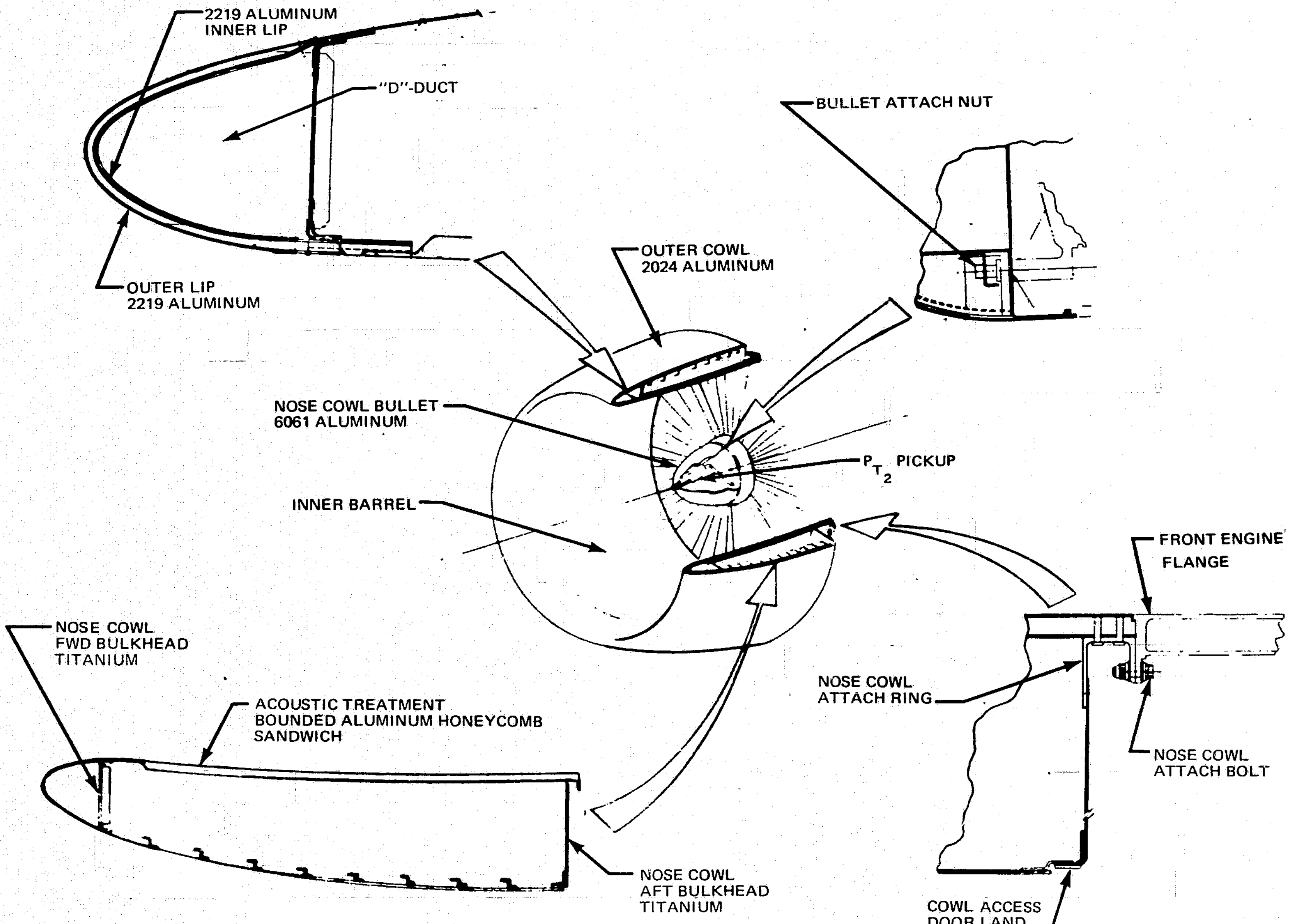


FIGURE 8. DC-9 REFAN NOSE COWL STRUCTURE

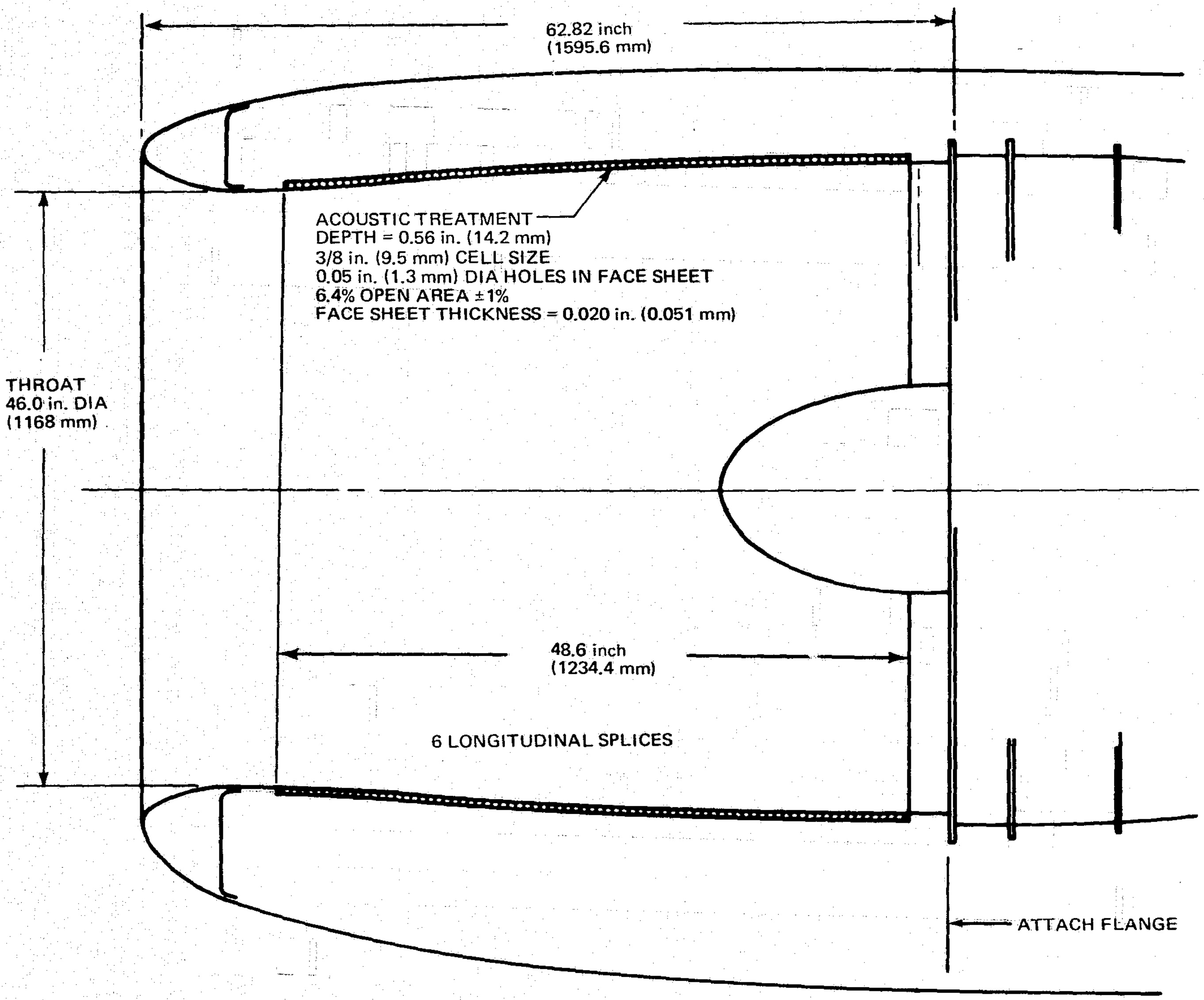


FIGURE 9. DC-9 REFAN INLET DUCT-SELECTED ACOUSTIC TREATMENT

The exhaust duct (figure 10) is interchangeable in either engine position and consists of two sections of duct joined together by a pair of back-to-back flanges. The forward section attaches to the engine M flange and incorporates fore and aft bulkheads to support the outer nacelle fairing. The aft section incorporates supports for the thrust reverser actuating cylinders and linkage which provides a load path to transfer the thrust reverser loads into the engine case. The acoustic treatment used in both sections is Inconel 625 Stresskin.

The thrust reverser system for the JT8D-109 engine was scaled-up version of the production DC-9 system and was designed to produce essentially the same total retarding effect on the airplane during normal landing deployment as the production DC-9 system.

The thrust reverser mechanism consists of target type reverser doors, a hydraulic actuating system, a mechanical control system, a structural support system, and an indicating system.

The reverser assembly is interchangeable and is oriented on each of the two forward exhaust duct segments (one for each engine) such that the upper reverser door directs the exhaust 0.262 rad (15 deg) from the vertical toward the airplane centerline while the lower reverser door directs the exhaust 0.262 rad (15 deg) from the vertical away from the airplane centerline. This feature is accomplished by using the rotation flange in the exhaust duct (figure 10) and has reduced foreign object damage due to reingestion on in-service DC-9 production airplanes.

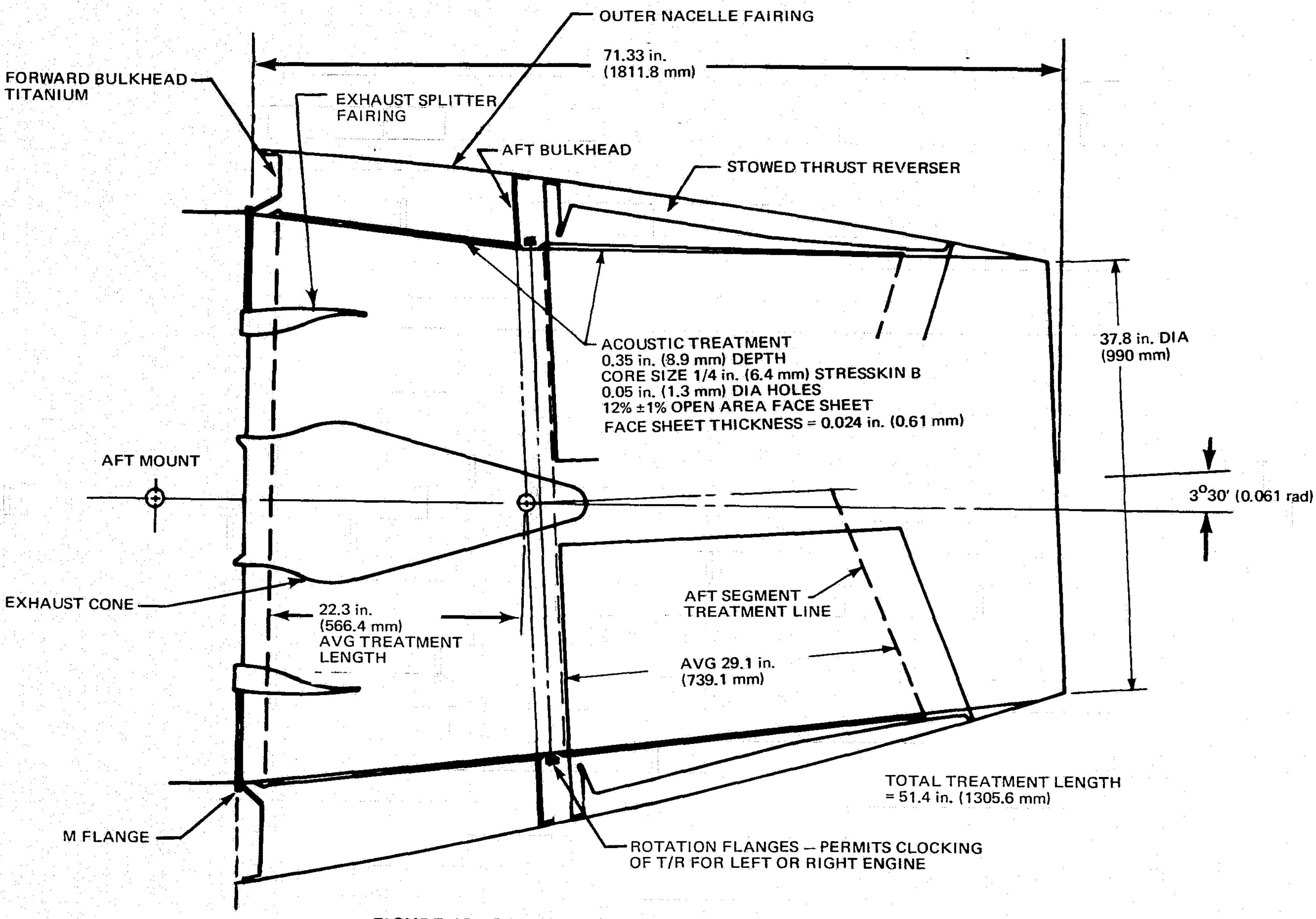


FIGURE 10. DC-9 REFAN JT8D-109 ENGINE EXHAUST DUCT

Engine and Nacelle Subsystem Development

The JT8D-109 engine and nacelle subsystem arrangement was identical to the production DC-9 systems. Table 1 indicates the extent to which the production DC-9 subsystem major components were either retained, modified, redeveloped or replaced.

Neutral engine piping and wiring redevelopment, component fit checks, and the thrust reverser assembly functional test was accomplished on the development fixture which consisted of a Douglas fixture and a Pratt and the Whitney Class III mockup engine (figure 11).

Engine installation development was accomplished at a savings in cost, material, and schedule by sequencing the development to use the flight pylon installed on the Refan airplane, instead of an accurately tooled pylon/fuselage simulation with the engine subsystem interface attach fittings.

When the airplane function checks were completed the class III mockup engine was removed from the Douglas fixture and installed on the left side of the airplane (figure 12). After which, the engine installation development was completed using the actual airplane pylon/fuselage interface connections.

Use of this procedure permitted complete engine installation development on both engine positions prior to the arrival of the JT8D-109 flight test engines. Upon arrival at the Douglas Long Beach facility the test engines were built up and installed on the Refan airplane.

TABLE 1

JT8D-109 VERSUS JT8D-9 ENGINE AND NACELLE SUBSYSTEM REQUIREMENTS

ITEM DESCRIPTION	RETAIN PRODUCTION ITEM(S)	MODIFY PRODUCTION ITEM(S)	REDEVELOP DUCTS, WIRING, ETC.	REPLACE
Electrical System				
Generator	X			
Generator Cooling Ducts	X			
J-Box and Support	X			
T/R Harness				X
Gen Pwr Harness		X		
Gen Cont Harness		X		
P/P Misc Harness		X		
Pylon F.D. Harness	X			
Constant Speed Drive	X			
CSD Hoses	X			
CSD Oil Cooler	X			
Hydraulic System			X	
Pump	X			
Hoses	X			
"Bridle" Supt Brkts	X			
Fuel System			X	
Eductor	X			
Crossover Pipe	X			
Controls System				
Throttle				X
Fuel Shutoff				X
Engine Indicating Systems		X		
Engine Pressure Ratio	X		X	
Engine Exhaust Gas Temp	X			
Engine Tachometer	X			
Fuel Flow and Fuel Used	X			
Power Supply, Regulated Frequency	X			
Fuel Inlet Pres Caution	X			
Fuel Filter Differential Pressure Caution	X			
Fuel Heater Control & Ind	X			
Low Engine Oil Pres Caution	X			
Engine Oil Strainer Caution	X			
Fuel Temperature	X			
Engine Oil Pressure	X			
Engine Oil Temp	X			
Engine Oil Quantity	X			
RAT Vs EPR Indicator		X		

TABLE 1 (Concluded)

JT8D-109 VERSUS JT8D-9 ENGINE AND NACELLE SUBSYSTEM REQUIREMENTS

ITEM DESCRIPTION	RETAIN PRODUCTION ITEM(S)	MODIFY PRODUCTION ITEM(S)	REDEVELOP DUCTS, WIRING, ETC.	REPLACE
Engine Bleed Air System				
8th Stage Manifold		X		
13th Stage Manifold		X		
8th Stage Check Valve		X		
Ice Protection				
Engine Anti-Icing Valve	X			
Cowl Anti-Icing Valve	X			
Thermostatic Valve	X			
Nose Cowl Ejector				X
13th Stage Pipe		X		
Engine Oil System	X		X	
Oil Pres X-mitter	X			
Oil Temp X-mitter	X			
Low Oil Pres SW	X			
Filter Lo Pres Caution	X			
Cooling & Ventilation		X		
Engine and Nacelle Drains	X	X		
Engine Starting System			X	
Starter	X			
Starter S/O Valve	X			
Starter Pneu Ducts				X

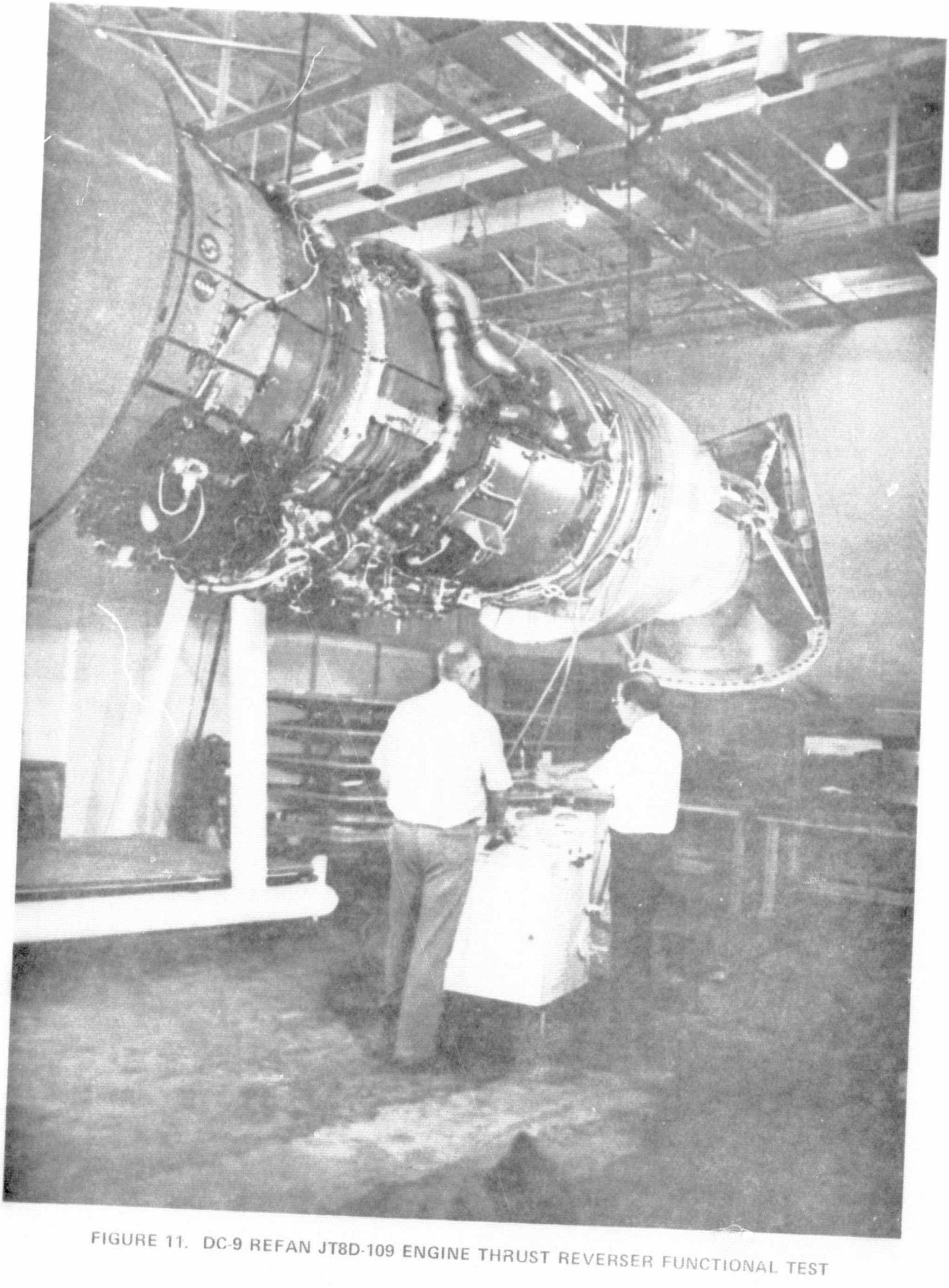


FIGURE 11. DC-9 REFAN JT8D-109 ENGINE THRUST REVERSER FUNCTIONAL TEST

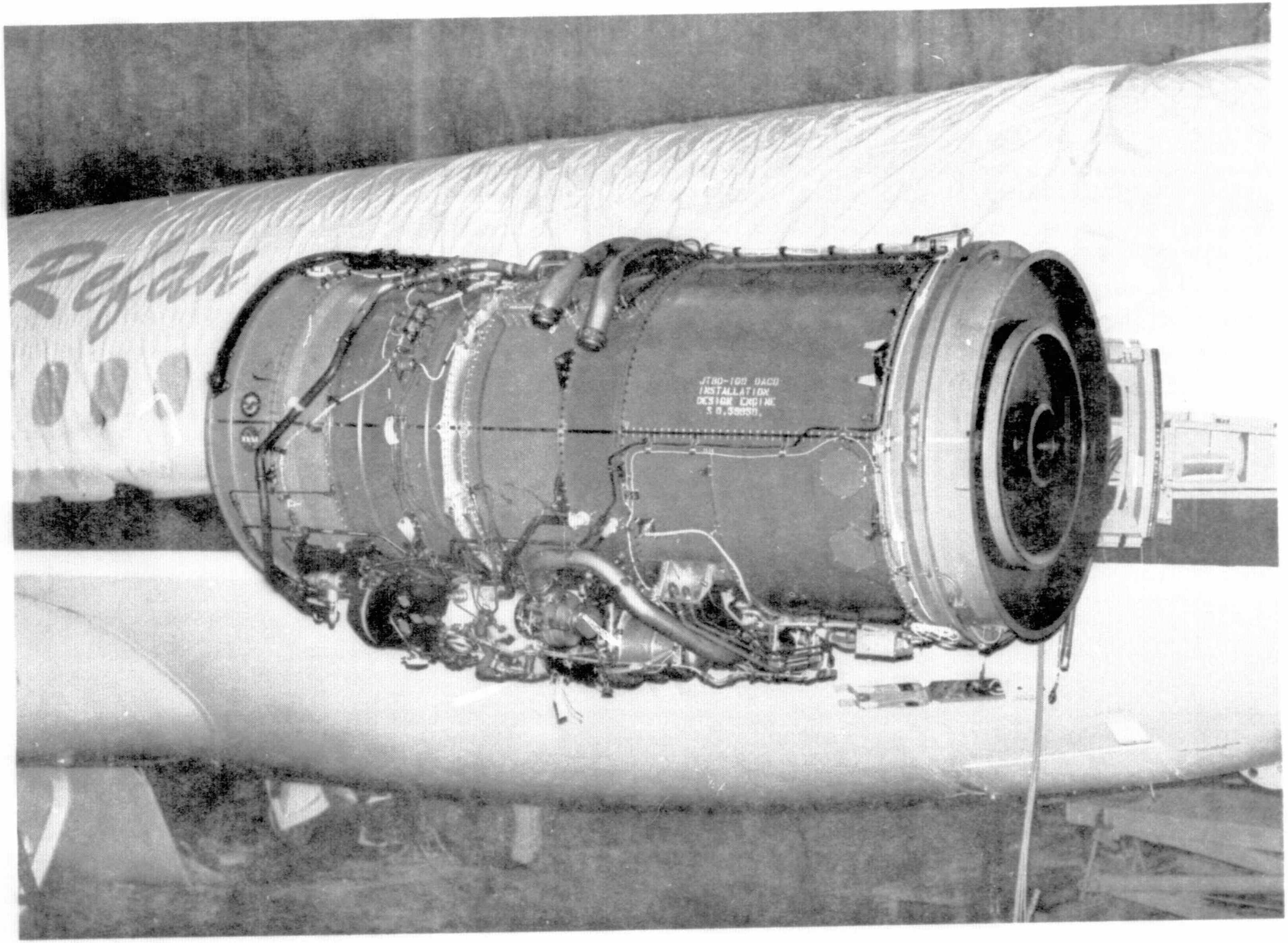


FIGURE 12. DC-9 REFAN CLASS III JT8D-109 MOCKUP ENGINE INSTALLED ON REFAN AIRPLANE LEFT PYLON

Fire Protection

The production DC-9 fire protection system was modified to accommodate the JT8D-109 engine installation. Fire barriers and seals were used for isolation and containment with detection and extinguishing provisions for control (figure 13).

To give maximum fire protection at points where the subsystems pass from the pylon into the fuselage, fire proof boxes were mounted on the fuselage skin at the fuel pipe, the 8th and 13th stage bleed air ducts, and the electrical connections. In addition, a plasma sprayed columbium burn-through barrier (located in the area of engine burner cans) was attached 10.1 mm (0.40 in.) outboard of the fuselage skin (figure 4).

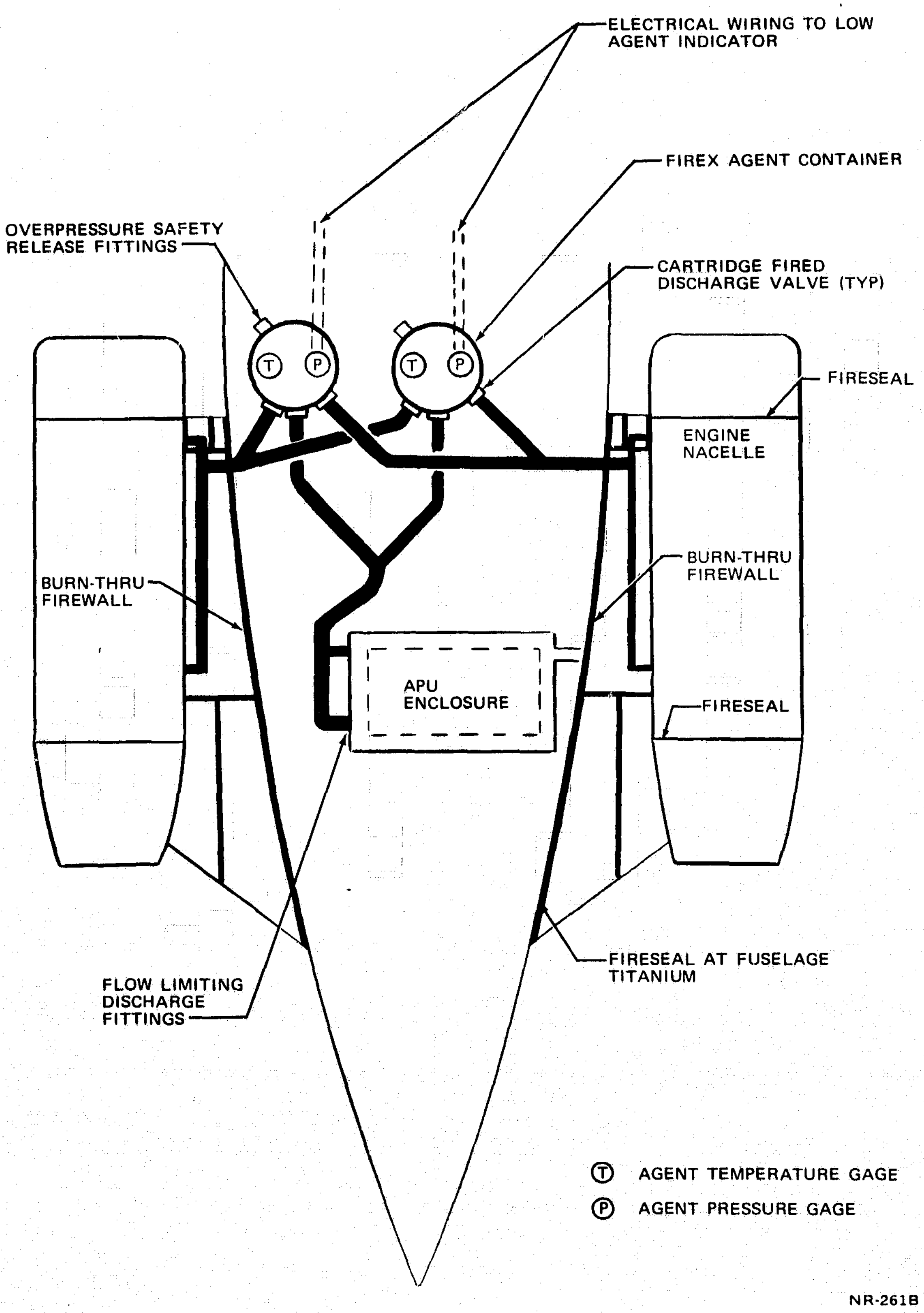


FIGURE 13. DC-9 REFAN JT8D-109 ENGINE FIREWALL AND FIREX SYSTEM

PERFORMANCE AND ANALYSIS

During the early design stages considerable analytical effort was required to support Refan hardware design and construction and ground and flight test planning.

Load, strength, and dynamic analyses were required for the redesign or modification to the nacelle, pylon, and fuselage. Dynamic analyses were also performed for airplane flutter, gust loads, and landing loads.

External aerodynamic analyses were required to define the geometric characteristics of a minimum size pylon and nacelle to enclose the JT8D-109 engine and accessories.

Inlet aerodynamic analyses were required to evaluate the performance characteristics of an inlet whose internal geometry was defined principally by acoustic and economic considerations rather than aerodynamic.

Exhaust system analyses were required to define exhaust duct lines of curvature that would produce low duct Mach numbers, enhance exhaust duct sound attenuation characteristics and yield good performance. Analytical methods were also helpful in evaluating the shape of the splitter that divides the fan and core streams up to the exhaust nozzle entrance.

JT8D-109 bare engine performance was estimated and compared directly to JT8D-9 engine performance. All performance estimates were based on JT8D engine computer decks supplied by Pratt and Whitney. The effects of engine installation losses were also evaluated with the computer decks.

Airplane performance analyses were required to define the takeoff field lengths, takeoff flight paths, and payload range characteristics of a DC-9-32 airplane powered by production JT8D-109 and JT8D-9 engines.

Test flights were conducted to establish performance levels of the Refan airplane with prototype flight test JT8D-109 engines, to verify design and analytical predictions and provide a basis for the structural optimization of a production retrofit design.

The flight test objectives, test procedures, test instrumentation, and the test data analysis and presentation were defined in the Refan program flight test plan, which was submitted and approved by NASA prior to the start of testing.

Installation and testing of the prototype flight engines was accomplished within the scope of normal procedures with no unusual problems. The engine operations were excellent and engine performance was very close to the predicted levels.

Final airplane performance analysis was completed after the engine manufacturer evaluated Ground Static and NASA Lewis Altitude Test data and updated the production JT8D-109 engine computer deck.

Engine Performance

The JT8D-109 engine is a derivative of the basic Pratt and Whitney Aircraft JT8D-9 turbofan engine. It is an axial flow two spool ducted turbofan engine with a mechanically coupled single stage fan and six low pressure compressor stages driven by a three stage turbine. The seven stage high pressure compressor is driven by a single stage turbine through concentric shafting. The burner section consists of nine separate chambers in an annular array. The turbine in temperature on a 15°C (59°F) day is 975°C (1789°F).

The annular fan duct delivers the fan air rearward where it is combined with the main engine air and discharged through a common jet nozzle. The compressor system generates a takeoff compression ratio of 15.5 and a bypass ratio of 2.12. A cross section comparison of the JT8D-109 and JT8D-9 engine and nacelle is depicted in figure 14.

The performance and physical characteristics of a production JT8D-109 and JT8D-9 are compared in table 2. The direct comparison of bare engine performance is based on conditions at the Pratt and Whitney Aircraft reference nozzle using a fuel lower heating value of 10 224 kg cal/kg (18,400 Btu/lb).

The installed engine performance of the production JT8D-109 and JT8D-9 engine is compared in figure 15 and 16. Performance comparisons between the JT8D-9 and JT8D-109 engines are shown for takeoff and cruise conditions. A direct comparison can be made between the two engine installations because of the identical reference nozzles and charging stations used by Pratt and Whitney Aircraft. The data presented includes all installation effects for normal operation. The installation losses applied to the JT8D-9 and JT8D-109 engines include the following: Douglas inlet, fan and compressor bleeds, power extraction, Douglas nozzle loss and nacelle drag.

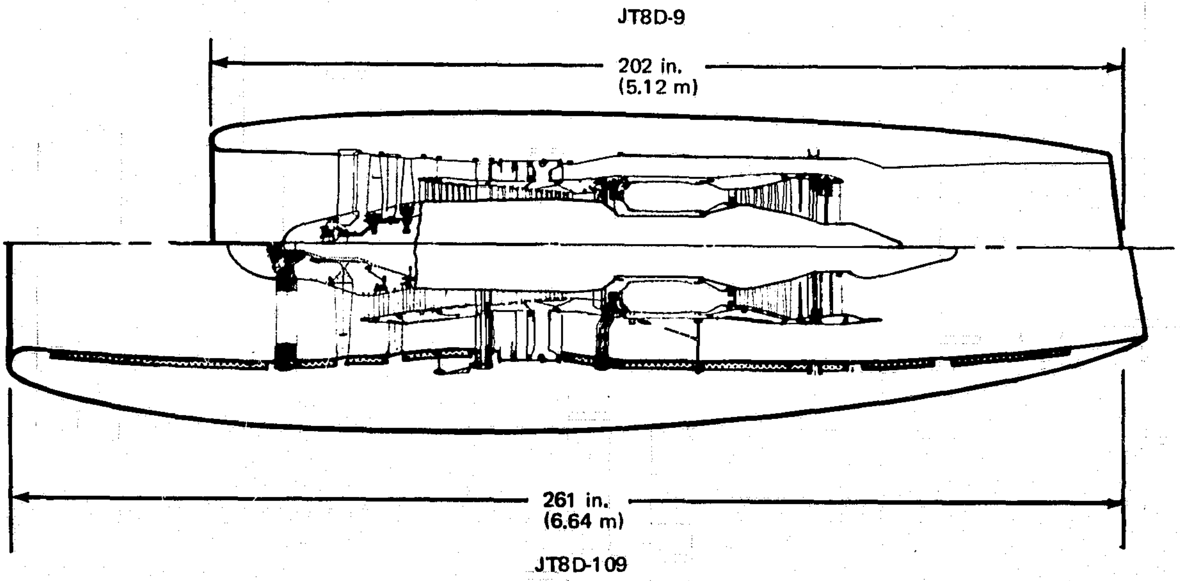


FIGURE 14. JT8D ENGINE/NACELLE COMPARISON

TABLE 2
BARE ENGINE CHARACTERISTICS COMPARISON

		JT8D-9*	JT8D-109**
TAKEOFF THRUST (SEA LEVEL STATIC, STANDARD DAY)	lb (N)	14,500 (64 500)	16,600 (73 840)
FAN TIP SPEED, SEA LEVEL STATIC TAKEOFF	ft/s (m/s)	1,420 (432.8)	1,567 (477.6)
BYPASS RATIO		1.05	2.12
MAXIMUM AIRFLOW	lb/s (kg/s)	340 (154)	510 (231)
FAN PRESSURE RATIO		1.97	1.66
MAXIMUM CRUISE THRUST –30,000 ft (9 144 m), 0.80 M	lb (N)	4,540 (20 195)	4,720 (20 996)
CRUISE TSFC – 30,000 ft (9 144 m), 0.80 M, 4,400 lb (19 571 N) THRUST	lb/hr/lb (kg/hr/N)	0.793 (0.0809)	0.781 (0.0796)
FAN TIP DIAMETER	in. (m)	40.5 (1.03)	49.2 (1.25)
OVERALL BARE ENGINE LENGTH (LESS SPINNER)	in. (m)	119.97 (3.047)	127.19 (3.231)
BARE ENGINE WEIGHT	lb (kg)	3,217 (1 460)	3,822 (1 734)

*BASED ON CCD 0219-01.1 WITH P&WA NOZZLE

**BASED ON CCD 0287-01.0 WITH P&WA NOZZLE

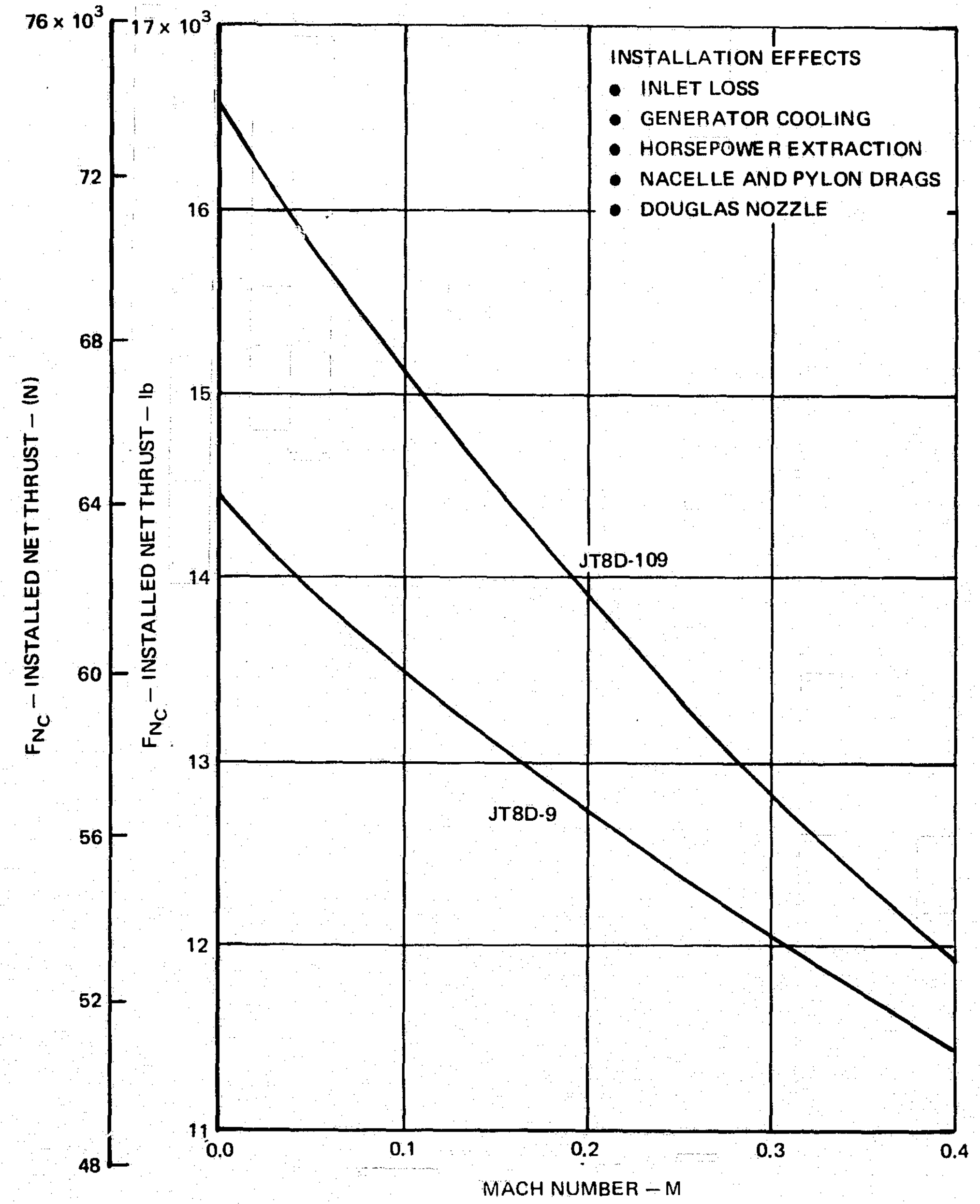
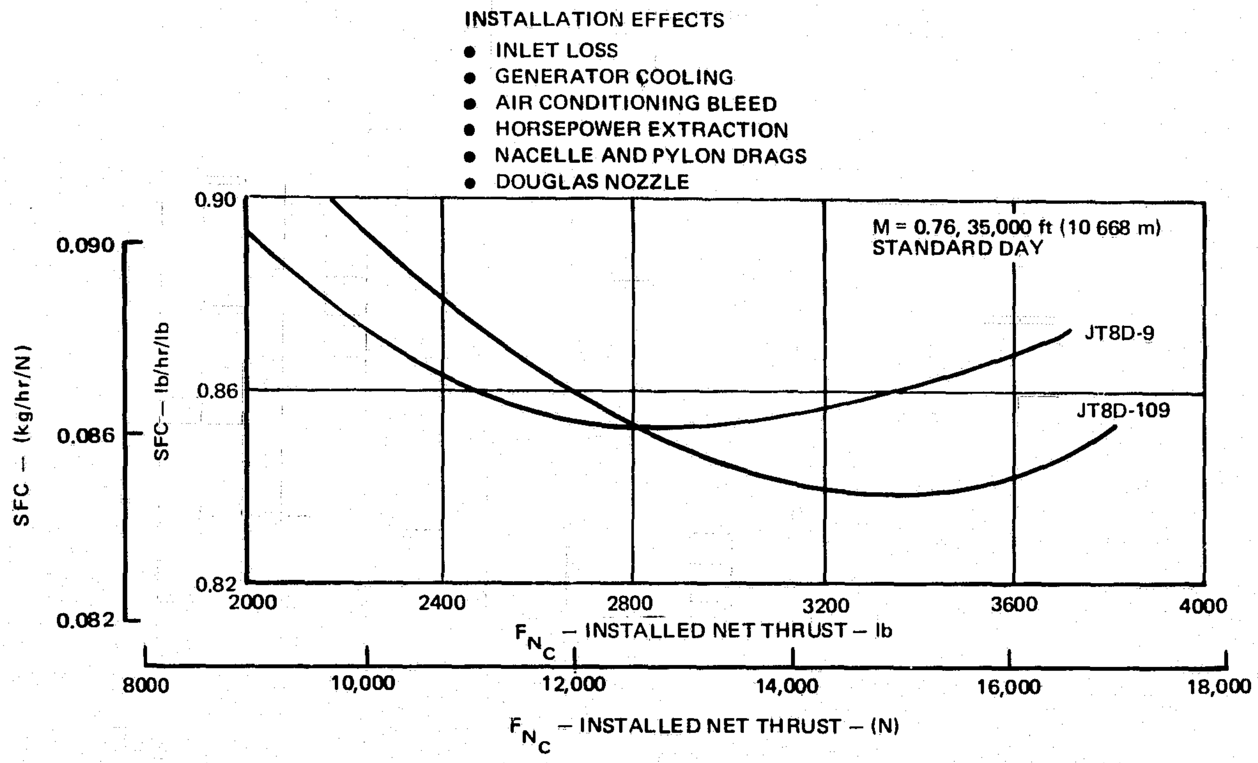


FIGURE 15. DC-9 REFAN INSTALLED ENGINE PERFORMANCE, TAKEOFF, SEA LEVEL, STANDARD DAY



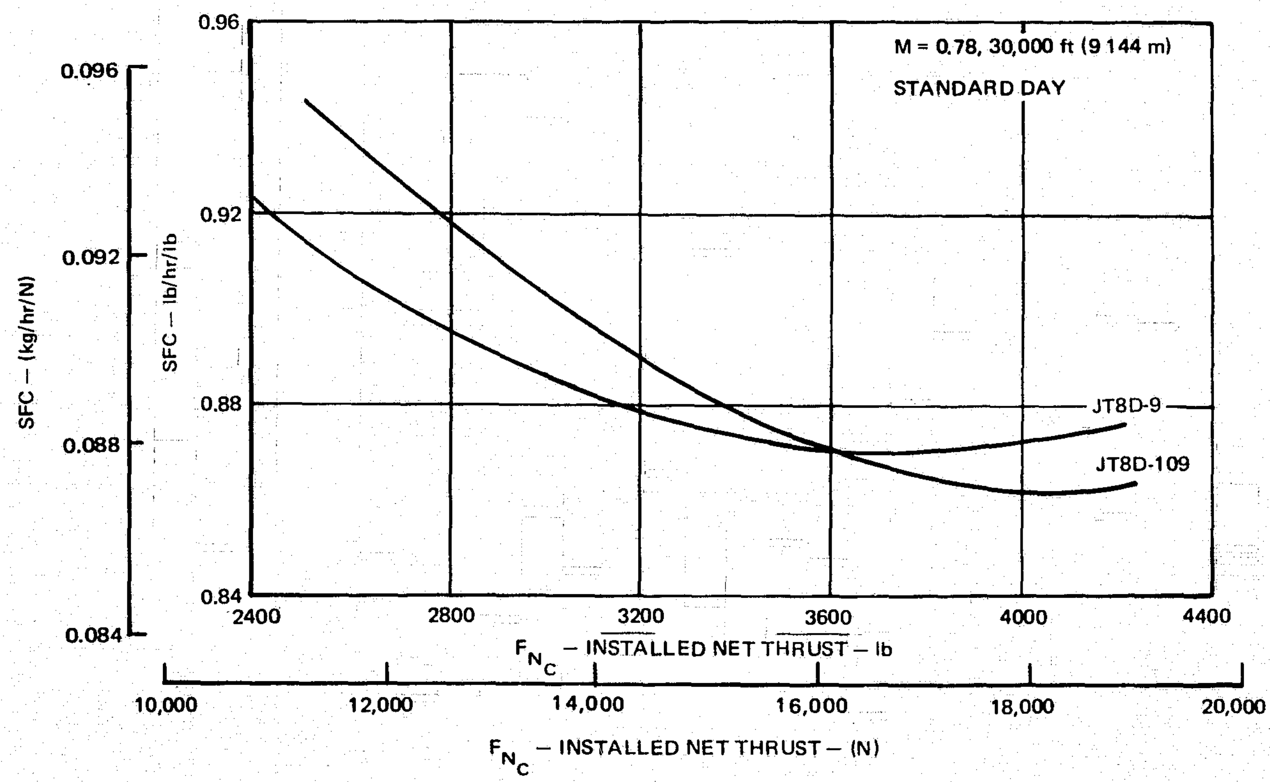


FIGURE 16. DC-9 REFAN INSTALLED CRUISE PERFORMANCE

Airplane Performance

The installation of the JT8D-109 engine results in an operational weight increase of 1 041 kg (2,294 lb) and an aft Operational Empty Weight (OEW) center of gravity shift of 6 to 7 percent M.A.C. A weight breakdown is presented in table 3 for the production DC-9-32 and the DC-9 Refan airplane. The weight increase is split about equally between the airframe and the engine. Retrofit weights are approximately 91 kg (200 lb) less than the flight test weights because of the incorporation of weight reduction items that were identified during the hardware design and through analyses of the flight test results.

A comparison of the DC-9-32 FAA takeoff field length as a function of takeoff gross weight is shown in figure 17 for the JT8D-109 and JT8D-9 engine installations. At sea level standard day conditions the additional thrust of the JT8D-109 engine results in about 2 040 kg (4,500 lb) additional takeoff gross weight capability for a given field length of which about one half is the increased OEW and one half is increased payload. Also, the airplane is not second segment climb limited (i.e., no reduction in flap setting, with its resulting greater field length, required to meet the engine-out climb gradient requirement). The minimum field length, as limited by airplane minimum control speed, is indicated in figure 17. The Refan configuration has an increase in ground minimum control speed of 1.5 m/s (2.9 knots).

Comparisons of the DC-9-32 payload range characteristics for the JT8D-9 and JT8D-109 engine installations for high speed cruise and long range cruise at 10 668 m (35,000 ft) altitude are presented in figures 18 and 19. High speed cruise is flown at the higher speed at which the specific range is 99 percent of the maximum nautical miles per pound attainable at the cruise weight. High speed climb and descent schedules are used with 0.78 Mach number cruise and long range climb and descent schedules are used with long range cruise. Domestic reserves are used with all cases. Maximum fuel capacity assumes the use of the 2 195 liter (580 gal) centerline fuel tank.

Breakdowns of the maximum range increments due to weight and SFC differences between the JT8D-9 and JT8D-109 powered versions of the DC-9-32 are shown in tables 4 and 5 for long range cruise at 10 668 m (35,000 ft) and 0.78 Mach number cruise at 9 144 m (30,000 ft), respectively. The breakdowns are shown for two payloads, 10 433 kg (23,000 lb) and 6 804 kg (15,000 lb), to illustrate both takeoff-gross-weight limited and fuel-capacity limited cases. As shown, the SFC and drag changes between the engine installations result in a small range gain for the DC-9 Refan; but the additional OEW results in a moderate range loss when the airplane is fuel-capacity limited and a substantial range loss when the airplane is takeoff-gross-weight limited.

Tables 6 and 7 show less than 1 percent increase in block fuel for the JT8D-109 powered DC-9 airplane with the typical mission payload 6 804 kg (15,000 lb) and 694 km (375 n.mi.) range, for both the long range cruise at 10 668 m (35,000 ft) and 0.78 Mach number cruise at 9 144 m (30,000 ft) cases.

TABLE 3

DC-9 PRODUCTION WEIGHT BREAKDOWN COMPARISON

	PRODUCTION CONFIGURATION			
	JT8D-9		JT8D-109	
	lb	(kg)	lb	(kg)
NOSE COWLS	212	(96)	624	(283)
ACCESS DOORS	436	(198)	550	(249)
THRUST REVERSERS	490	(222)	884	(401)
ENGINE MOUNTS	100	(45)	114	(52)
EXHAUST SYSTEMS	282	(128)	522	(237)
APRON STRUCTURES	120	(54)	146	(66)
PYLONS	450	(204)	514	(233)
FUSELAGE	84	(38)	110	(50)
ACCESSORIES	480	(218)	480	(218)
SYSTEMS	650	(295)	514	(233)
TOTAL WEIGHT PER AIRCRAFT	3,304	(1 498)	4,458	(2 022)
ENGINES 2 PER P&WA WEIGHT	6,504	(2 950)	7,644	(3 467)
MANUFACTURER'S EMPTY WEIGHT	55,216	(25 046)	57,510	(26 086)
OPERATIONAL EMPTY WEIGHT	59,076	(26 796)	61,370	(27 837)
MAXIMUM ZERO FUEL WEIGHT	87,000	(39 463)	87,000	(39 463)
MAXIMUM LANDING WEIGHT	99,000	(44 906)	99,000	(44 906)
MAXIMUM TAKEOFF WEIGHT	108,000	(48 988)	108,000	(48 988)
MAXIMUM TAXI WEIGHT	109,000	(49 442)	109,000	(49 442)

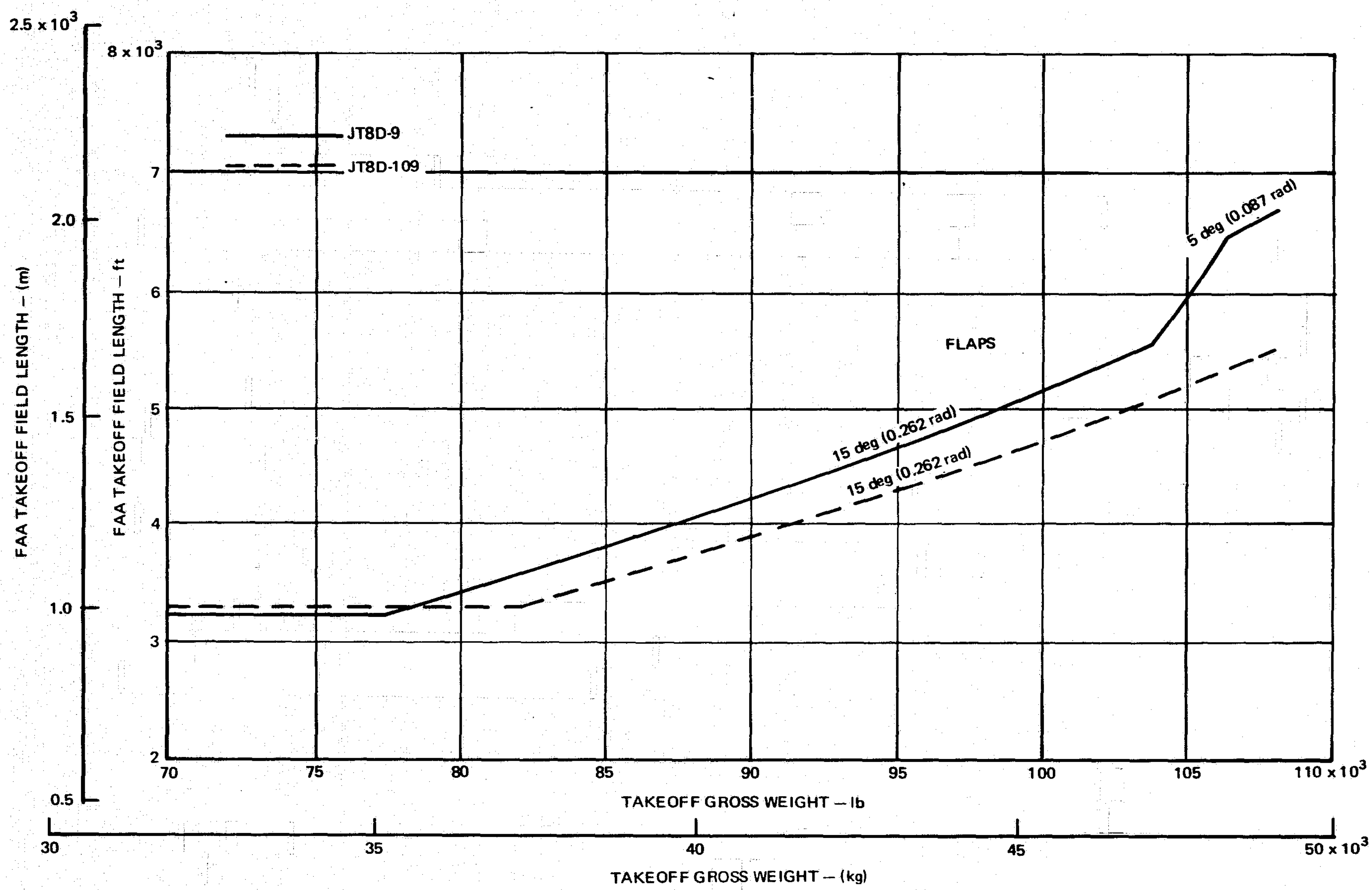


FIGURE 17. DC-9 REFAN TAKEOFF PERFORMANCE, SEA LEVEL, STANDARD DAY, BLEEDS OFF

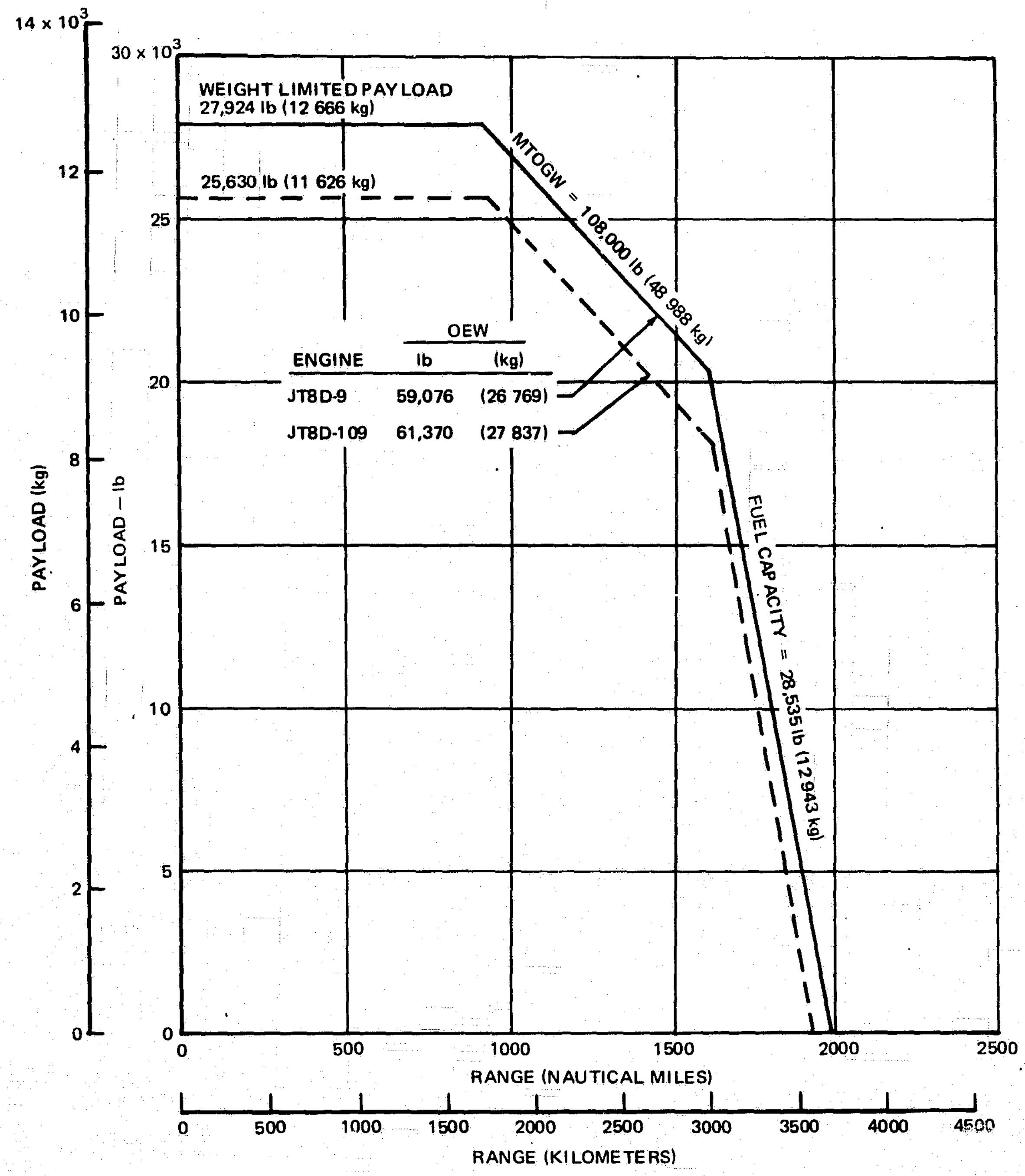


FIGURE 18. DC-9 REFAN PAYLOAD-RANGE CAPABILITY, CRUISE AT M = 0.78 AND hp = 35,000 ft (10 668 m)

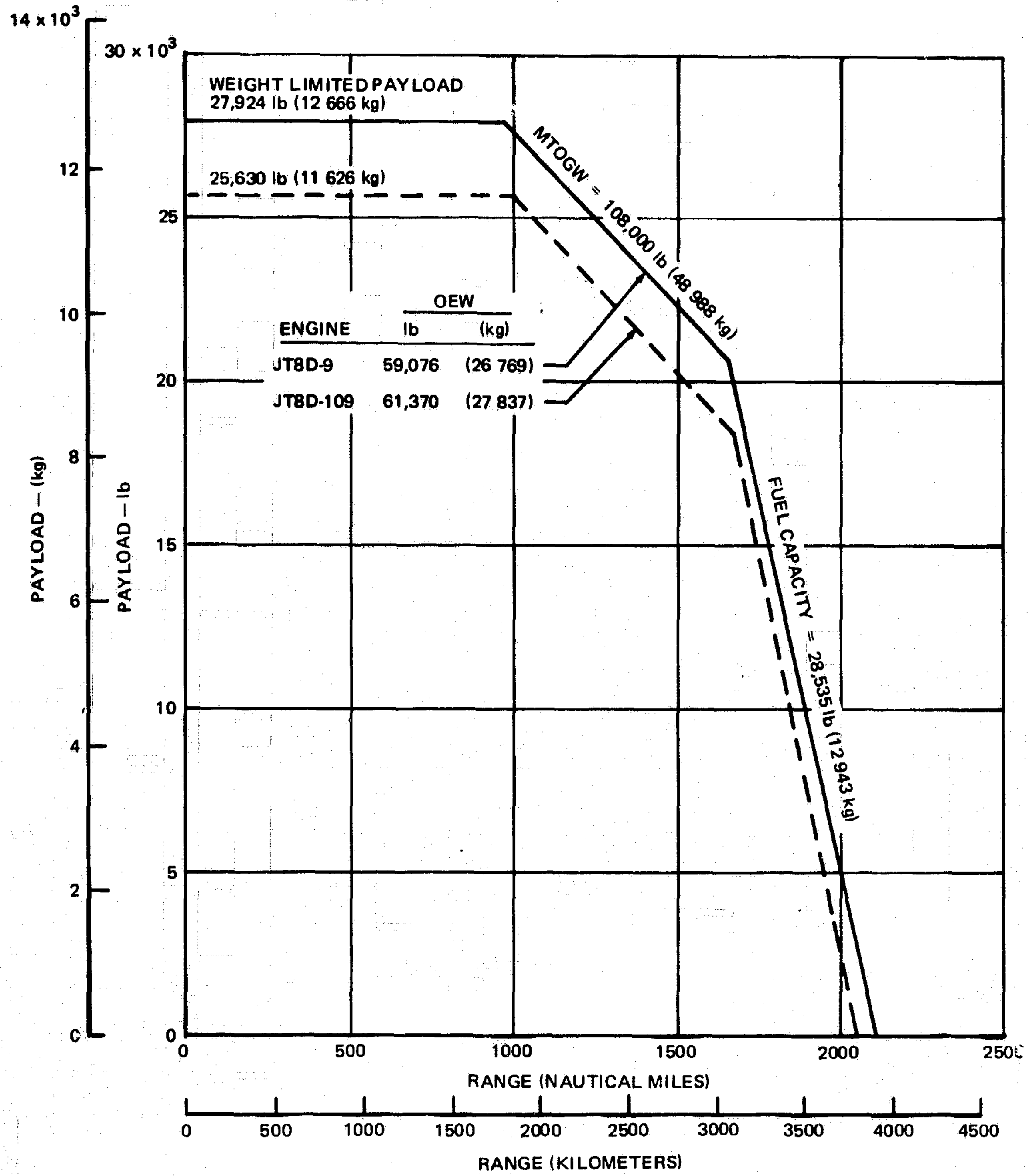


FIGURE 19. DC-9 REFAN PAYLOAD-RANGE CAPABILITY, LONG RANGE CRUISE AT 35,000 ft (10 668 m)

TABLE 4

RANGE CHANGE FOR THE JT8D-109 RELATIVE TO THE JT8D-9

LONG RANGE CRUISE AT 35,000 ft (10 668 m)

COMPONENTS AFFECTING MAXIMUM RANGE	PAYLOAD = 15,000 lb (6 804 kg) (limited by max fuel capacity)	PAYLOAD = 23,000 lb (10 433 kg) (limited by max takeoff gross weight)
SFC (Including effect of Nacelle and Pylon Drag Changes)	+16 n. mi. (+29 km)	+24 n. mi. (+44 km)
WEIGHT INCREASE	-45 n. mi. (-83 km)	-214 n. mi. (-396 km)
TOTAL CHANGE	-29 n. mi.	-190 n. mi. (-352 km)

TABLE 5

RANGE CHANGE FOR THE JT8D-109 RELATIVE TO THE JT8D-9

CRUISE AT M = 0.78 AT 30,000 ft (9 144 m)

COMPONENTS AFFECTING MAXIMUM RANGE	PAYLOAD = 15,000 lb (6 804 kg) (limited by max fuel capacity)	PAYLOAD = 23,000 lb (10 433 kg) (limited by max takeoff gross weight)
SFC (Including effect of Nacelle and Pylon Drag Changes)	+2 n. mi. (+4 km)	+14 n. mi. (+26 km)
WEIGHT INCREASE	-29 n. mi. (-54 km)	-190 n. mi. (-352 km)
TOTAL CHANGE	-27 n. mi. (-30 km)	-176 n. mi. (-326 km)

TABLE 6

PERFORMANCE CHANGE FOR THE JT8D-109 RELATIVE TO THE JT8D-9

LONG RANGE CRUISE AT 35,000 FT (10 668 m)

PAYLOAD = 15,000 LB (6 804 kg)

RANGE	375 n.mi. (694 km)
FUEL BURNED INCREMENT	+16 lb (+7 kg)
BLOCK SPEED INCREMENT	-0.3 knots (-0.6 km/hr)
TAKEOFF FIELD LENGTH INCREMENT (SEA LEVEL, STANDARD DAY)	-115 ft (-35 m)
TOTAL FUEL BURNED (JT8D-109)	5,926 lb (2 552 kg)

TABLE 7

PERFORMANCE CHANGE FOR THE JT8D-109 RELATIVE TO THE JT8D-9
CRUISE AT M = 0.78 AT 30,000 FT (9 144 m)
PAYLOAD = 15,000 LB (6 804 kg)

RANGE	375 n.mi (694 km)
FUEL BURNED INCREMENT	+52 lb (+24 kg)
TAKEOFF GROSS WEIGHT INCREEMENT	+2,412 lb (+1 094 kg)
BLOCK SPEED INCREMENT	+1.9 knots (+3.5 km/hr)
TAKEOFF FIELD LENGTH INCREMENT	-105 ft (-32 m)
TOTAL FUEL BURNED (JT8D-109)	6,477 lb (2 938 kg)

Airplane Stability and Control

The stability and control characteristics of the DC-9 Refan airplane were evaluated to determine the affect of the installation of the larger diameter JT8D-109 engine and nacelle, the reduced span pylon and weight increases.

The Refan airplane demonstrated stall characteristics similar to the DC-9-30 production airplane with no change in characteristics due to the installation of the JT8D-109 engine.

The static longitudinal stability appears to be slightly less than that of the production DC-9-30. However, the stability of the Refan configuration is considered sufficient to meet the requirements of previous production airplane certification tests and complies with production airplane airworthiness requirements.

The longitudinal control characteristics of the Refan airplane are not significantly changed from that of the production DC-9-30 and comply with production airplane airworthiness requirements.

The Refan airplane longitudinal trim characteristics are unchanged from that of the production DC-9-30 in the landing configuration and slightly more airplane nose-up in the cruise configuration. The Refan trimmability does comply with production airplane airworthiness requirements.

The Refan airplane air and ground minimum control speeds indicate little or no significant change from those of the production DC-9-30; and the controllability with both symmetrical and asymmetrical reverse thrust under all conditions tested was acceptable.

Airplane/Prototype Engine Performance

The DC-9 Refan airplane and flight test prototype JT8D-109 engine Performance was evaluated with respect to the production (DC-9-30/JT8D-9) airplane.

Test flights were conducted to establish the performance levels of the airplane and engine during takeoff, climb, cruise and landing with reverse thrust. Engine performance was evaluated during suction fuel feeding, windmill and ground engine starts, snap throttle retards, jam accelerations, airplane stall, high sideslip angles and abused takeoffs. Airplane/engine subsystem performance (ground and flight) was also evaluated.

Measured DC-9 Refan airplane takeoff acceleration data showed good agreement when compared with FAA approved production DC-9 Series 30 data.

Figure 20 presents the incremental differences between the flight measured Refan airplane climb data and production DC-9 Series 30 climb results as a function of climb gradient. The estimated incremental difference shown accounts for the increased nacelle skin friction drag, increased windmilling engine drag, and decreased lateral trim drag resulting from a smaller thrust moment arm for the JT8D-109 engine installation. The flight-measured data shows good agreement with the estimated incremental difference for each of the climb conditions.

The net result of climb performance associated with the Refan installation, including the improvement due to the increased thrust available and the penalty due to the increased thrust-to-weight ratio required is an 8 percent improvement in second segment and approach limiting weights and a 5 percent improvement in enroute limiting weight.

The cruise performance increment for installing JT8D-109 engines was evaluated based on drag and range factor increments. The JT8D-9 powered DC-9-30 production airplane drag is based on the composite drag of three separate airplanes. The range factor is also based on the average of three separate airplanes, all powered by JT8D-9 engines.

Figure 21 shows the measured drag increase at four W/δ's due to installing the JT8D-109 engine. The four W/δ's tested are representative of cruise operation at altitudes of 6 096 m (20,000 ft), 8 829 m (29,000 ft), 9 449 m (31,000 ft) and 10 668 m (35,000 ft) higher W/δ for higher altitude . The data points indicate that the drag penalty is about as estimated (skin friction and form drag only), about a 2 percent increase in airplane drag. This is not Mach number dependent for W/δ = 90 700 kg (200,000 lb), 136 100 kg (300,000 lb), or 158 800 kg (350,000 lb); only at W/δ= 181 400 kg (400,000 lb) is there any indication of the favorable interference (effect of engine stream tube reducing wing compressibility drag) that was measured in the wind tunnel.

Figure 22 shows the measured range factor reduction at four W/δ's for installing JT8D-109 engines. For the important operating conditions (M_0 = 0.75 - 0.78) the range factor is reduced by about 5 to 7 percent.

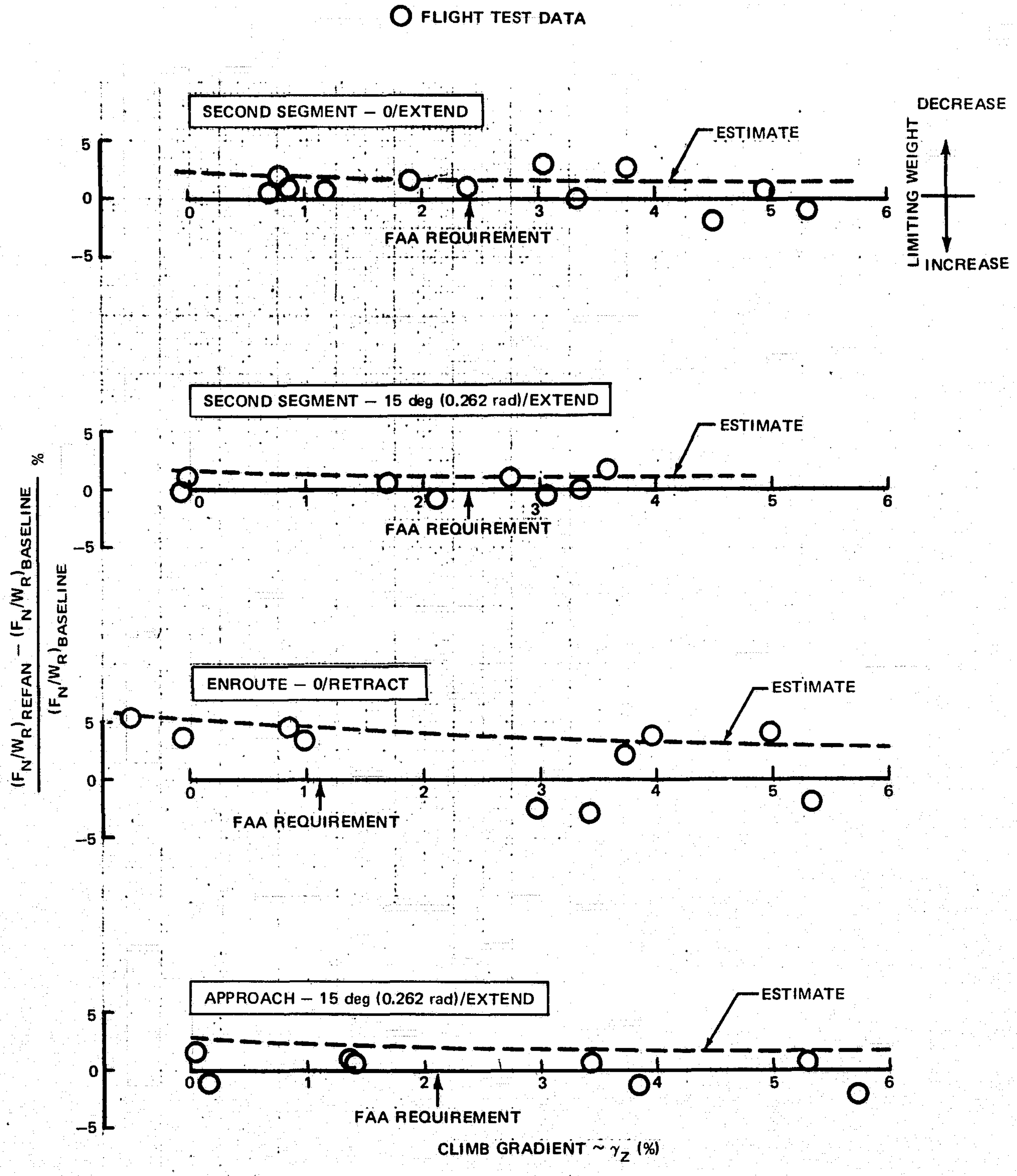


FIGURE 20. DC-9 REFAN CLIMB PERFORMANCE

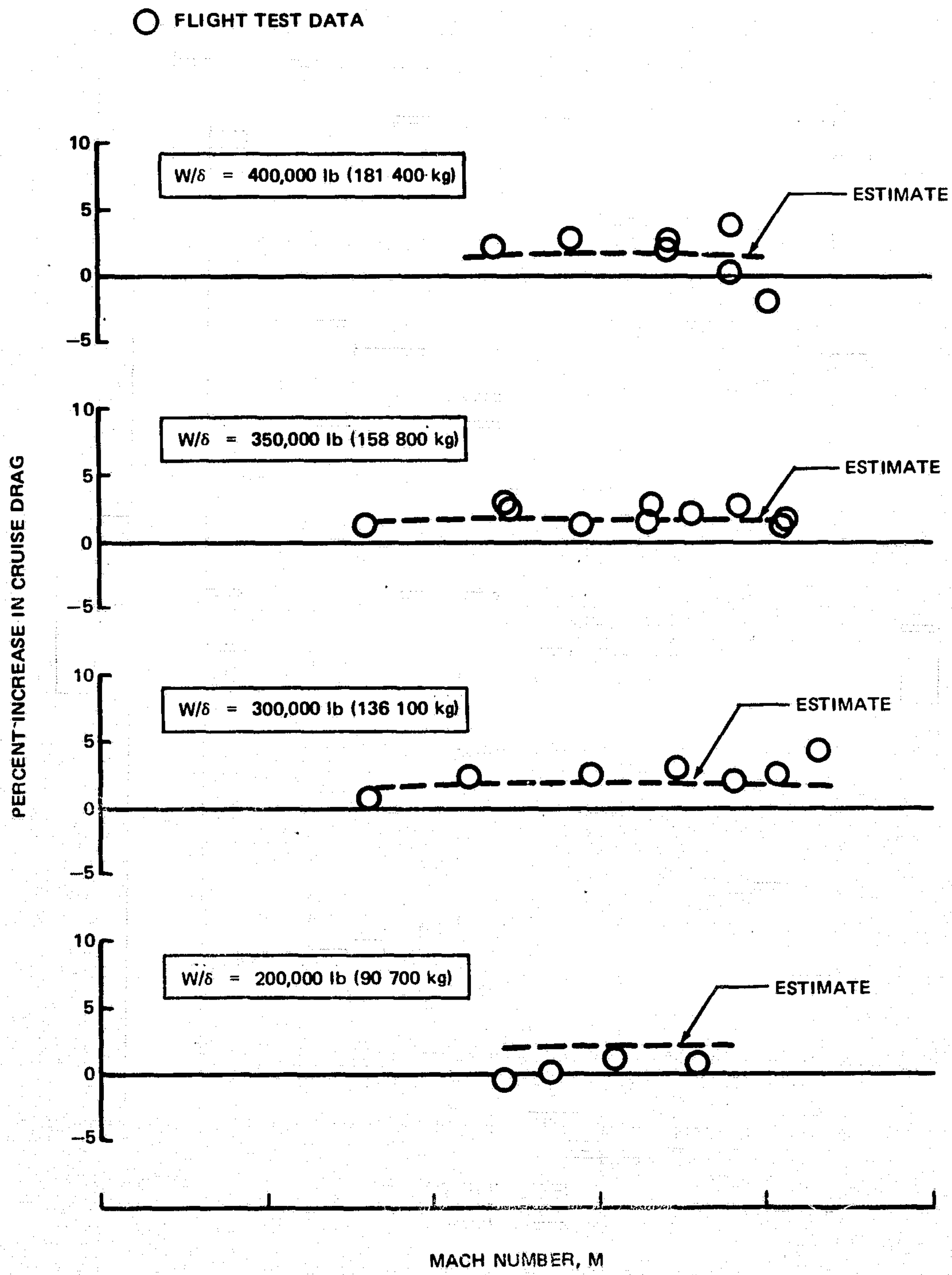


FIGURE 21. DC-9 REFAN CRUISE DRAG CHARACTERISTICS

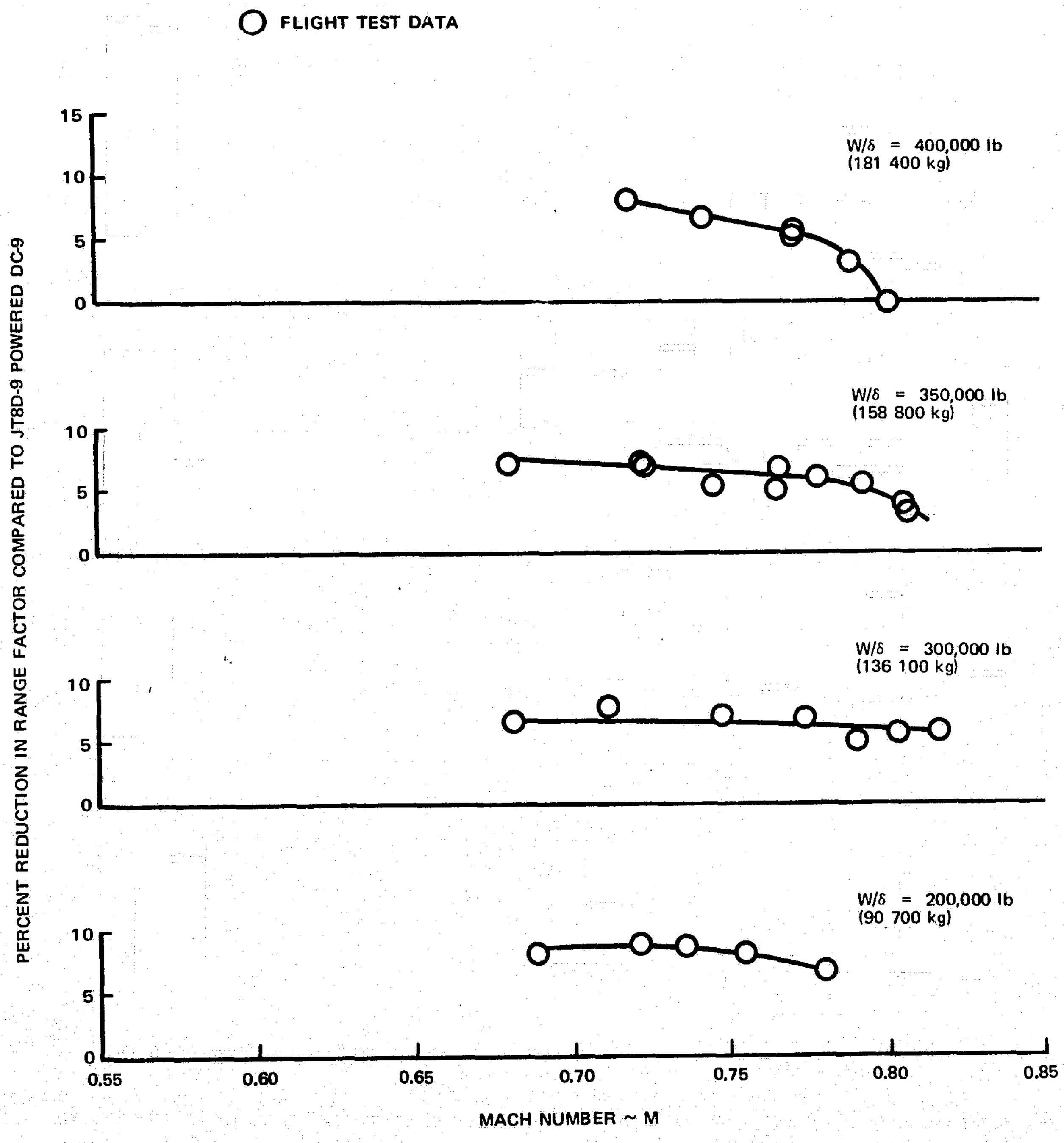


FIGURE 22. DC-9 REFAN RANGE FACTOR CHARACTERISTICS

About 2 percent is due to the increased drag of the larger nacelle. The balance (3-5 percent) is due to the poorer SFC of the prototype JT8D-109 engines. The range factor decrement is about one percent or so worse at W/δ = 90 700 kg (200,000 lb) due to the poorer SFC of the JT8D-109 prototype engine at the lower thrust settings.

In the Mach number range of primary interest, the drag increase for installing the larger Refan nacelle is about 2 percent. Only at 181 400 kg (400,000 lb) W/δ is the favorable influence of the larger engine stream tube sufficiently strong to reduce this increment.

During the thrust reverser performance evaluation normal reverse thrust operation was demonstrated at speeds below the operational cutback speed of 30.87 m/s (60 knots) with acceptable engine operation; and the peak empennage temperatures remained below the maximum allowable 121°C (250°F) for the aluminum skin.

No signs of engine instability were noted by the pilots while the maximum climb thrust maneuver utilizing fuel suction feed was being conducted. Engine ground starting characteristics were satisfactory with little or no change from other JT8D versions. The low speed inflight starting envelope was also verified to be satisfactory.

Engine response to throttle inputs was acceptable for the ground and inflight acceleration deceleration tests. During the slow down with MCT stalls, the high angle of attack evaluation, the abused takeoff maneuver, and the high angles of sideslip evaluation no abnormal engine operating characteristics were noted.

However, the right engine (S/N 666996) appeared to have less stall margin than the left (S/N 666995) by the occurrence of occasional compressor stalls during the approach to or recovery from airplane stalls.

The airplane/engine subsystem performance tests showed that the JT8D-109 engine nacelle compartment ventilation and component cooling requirements were satisfied for ground and inflight conditions. The JT8D-109 engine generator and CSD cooling systems were demonstrated satisfied for ground and inflight conditions. The JT8D-109 engine generator and CSD cooling systems were demonstrated satisfactorily for the critical (100% load) ground idle condition and for all inflight conditions.

The Refan cowl ice protection system flight evaluation shows that the system provides ice protection performance which is equal to or in excess of predictions. System design similarities with the certified production DC-9 system and the conservative nature of the analytical method indicate that the DC-9 Refan cowl ice protection system can be operated without restrictions.

Airplane Structural Integrity and Dynamics

Structural and dynamic analyses were performed during Phase II of the Refan Program to substantiate three basic program requirements: (1) The new nacelle and thrust reverser hardware and the modifications to the airplane structure were required to be flightworthy and certifiable to the Federal Aviation Regulations; (2) The DC-9 with JT8D-109 engine installed would meet or exceed required flutter speed margins; (3) The airplane in the Refan flight test configuration would qualify for an experimental flight test permit to be issued by the FAA.

In addition to the analyses performed in Phase II, ground tests were conducted prior to the flight test for verification of certain analytical predictions. These tests included an airplane ground vibration test (GVT), thrust reverser cycling to maximum reverse power, cabin pressurization and engine runup to takeoff power. Strain gauges and accelerometers were installed on primary structural components to monitor load levels, deflections and accelerations during the ground tests and subsequent flight tests.

The GVT results verified that the airplane normal modes or vibration were not significantly changed due to the Refan modifications. Likewise, the damping characteristics compared well with those of the basic production airplane.

Evaluation of the data from the ground and flight tests was accomplished to the extent that significant parameters were compared with analytical results. All pertinent data which were collected during the tests have been filed for future reference in the event a production program is initiated. The primary objective will be to use the test data to optimize the structural weight of the Refan hardware. Except for potential weight savings, the test results indicate that the structural configuration of the Refan hardware is satisfactory for use as a production retrofit of DC-9 airplane.

Structural and aerodynamic damping flight tests were conducted to substantiate the flutter integrity of the Refan airplane and to obtain frequency and damping response data to show correlation with analytical results. The test data shows that the DC-9-31 with JT8D-109 engines exhibited the same or slightly improved damping characteristics compared to the production airplane. Likewise, there were no instabilities or excessive vibration within the demonstrated flight envelope.

FLYOVER NOISE

The DC-9 Refan flyover-noise tests were conducted in compliance with FAR Part 36 and consisted of actual and simulated takeoff, approach flights including two segment approaches, and correction flyover flights. A total of 48 runs (aircraft flyovers) were made to simulate takeoff including takeoff with cutback; 47 runs (aircraft flyovers) were made to simulate approach including two segment approaches.

The tests were performed at the Douglas Aircraft Company flight test facilities at Yuma International Airport, Yuma, Arizona. The Yuma test site has the ground handling equipment, weather conditions, and a 4 054 m (13,500 ft) runway that satisfy the requirements of the test program. It also has a Douglas maintained CAT II ILS and a Laser Tracking system.

The Refan flyover-noise tests provided information to determine FAR Part 36 noise levels, EPNL and dB(A) distance maps, community noise contours, lateral noise attenuation, effects of air turbulence on sound propagation, and ground reflection effects on the spectra of measured flyover noise.

Additional flyover-noise tests of the DC-9-32 (C9A) and the Refan aircraft were conducted. The tests consisted of takeoff tests (with thrust cutback), landing approach tests, and correction flyovers for the C9A. Alternating the C9A runs with the DC-9 Refan permitted noise levels to be measured under similar conditions; however, the test weather for these tests was outside the window specified in FAR Part 36.

Noise Levels at FAR Part 36 Locations

The effective perceived noise levels (EPNL) at the FAR Part 36 conditions for sideline, takeoff with and without cutback, and approach flights for the Refan airplane were determined. These data are compared to the noise levels obtained from tests conducted in October 1974 as a part of the intermix certification of the DC-9-30 airplane. The takeoff gross weight was 48 988 kg (108,000 lb) and the landing weight was 44 906 kg (99,000 lb). The statistical 90 percent confidence limits associated with the Refan noise levels are included.

	Refan (JT8D-109)	Baseline (Oct '74) (JT8D-9 H/W)
	Effective Perceived Noise Levels (EPNdB)	
Sideline	95.3 ± 0.3	99.8
Takeoff	96.2 ± 0.6	102.7
Takeoff with Cutback	87.5 ± 0.3	97.4
Approach		
Flaps = 0.873 rad (50 deg)	97.4 ± 0.3	103.0
Flaps = 0.611 rad (35 deg)	95.7 ± 0.4	100.9

H/W = Hardwall

The noise levels for the limited flyover noise tests of the C9A compared to the Refan when flown alternately under similar conditions were determined and are tabulated below.

	Refan (JT8D-109)	C9A (JT8D-9 H/W)
	Effective Perceived Noise Levels (EPNdB)	
Takeoff with Cutback	88.0	95.7
Approach flaps = 0.873 rad (50 deg)	97.9	106.1

The FAR Part 36 noise levels, listed above, were calculated using aerodynamic reference conditions without pitch limit for the Refan airplane and with a 0.272 rad (15.6 deg) pitch limit for the baseline and C9A airplanes. The pitch limit for the baseline and C9A airplanes was used in order to be consistent with existing certified hardwall noise levels.

Airport Community Noise

Contours of effective perceived noise level (EPNdB) for single takeoff and approach operations of a DC-9 airplane powered by the JT8D-9 engine with hardwall nacelles and the JT8D-109 engine with Refan nacelles were developed The contour lines were generated by a method that determined points on the ground that were equidistant from the flight path. The sound path distance was adjusted by a procedure that included empirically derived corrections for ground-to-ground noise attenuation and airplane noise shielding. Also included were the effects of time-duration increase during ground roll and the increased inlet and jet noise at low forward velocities. The contours were generated for reference day conditions of 25°C (77°F) and 70 percent humidity.

The noise contours were generated using noise-level variation with distance obtained from the EPNL-vs-distance curves and the associated aerodynamic performance in the form of a flight path. Both the hardwall and Refan DC-9 flight paths were constructed using a 0.349 rad (20 deg) pitch limit.

Two airplane operational cases were considered, and representative 90 and 95 EPNdB contours were developed comparing the Series 30 DC-9 equipped with JT8D-9 engines and hardwall nacelles with the DC-9 Refan. Flight paths considered for each airplane are (1) full-thrust takeoff and 0.052 rad (3 deg) glideslope approach, (2) full-thrust takeoff and two segment 0.105/0.052 rad (6/3 deg) glideslope approach, (3) takeoff with cutback and 0.052 rad (3 deg) glideslope approach and (4) takeoff with cutback and two-segment 0.105/0.052 rad (6/3 deg) approach.

The first case was for FAR Part 36 operational requirements of maximum takeoff and landing gross weights of 48 988 kg (108,000 lb) and 44 906 kg (99,000 lb) respectively. The contours generated represent the maximum noise exposures that would occur around airports.

The second case was for a typical mission with an intermediate stop between two 694 km (375 n. mi.) stage lengths where the airplane was not fueled at the intermediate stop. The landing gross weight of the Refan airplane at the intermediate stop was 40 550 kg (89,400 lb) and the takeoff gross weight was 40 425 kg (89,210 lb). For the same typical mission the takeoff gross weight of the hardwall airplane was 39 332 kg (86,710 lb) and the landing gross weight was 39 464 kg (87,000 lb). The typical mission contours are more representative of the takeoff and landing noise levels that might occur during daily operations between two 694 km (375 n. mi.) stage lengths.

The contour areas are summarized in table 8 for both cases considered.

TABLE 8
CONTOUR AREA SUMMARY

MAXIMUM GROSS WEIGHT CONFIGURATION	AREA, SQUARE MILES (sq km)			
	DC-9 PRODUCTION		DC-9 REFAN	
FLIGHT CONDITION	90 EPNdB	95 EPNdB	90 EPNdB	95 EPNdB
TAKEOFF – 3-DEGREE APPROACH	15.3 (39.6)	6.9 (17.9)	9.3 (24.1)	3.4 (8.8)
TAKEOFF/CUTBACK – 3-DEGREE APPROACH	8.6 (22.3)	4.2 (10.9)	5.0 (13.0)	2.8 (7.3)
TAKEOFF – 2-SEGMENT APPROACH	15.0 (38.9)	6.8 (17.6)	9.2 (23.8)	3.4 (8.8)
TAKEOFF/CUTBACK – 2-SEGMENT APPROACH	8.3 (21.5)	4.2 (10.9)	4.9 (12.7)	2.8 (7.3)

TYPICAL MISSION CONFIGURATION	AREA, SQUARE MILES (sq km)			
	DC-9 PRODUCTION		DC-9 REFAN	
FLIGHT CONDITION	90 EPNdB	95 EPNdB	90 EPNdB	95 EPNdB
TAKEOFF – 3-DEGREE APPROACH	11.2 (29.0)	5.2 (13.5)	7.4 (19.2)	2.7 (7.0)
TAKEOFF/CUTBACK – 3-DEGREE APPROACH	4.7 (12.2)	3.0 (7.8)	3.8 (9.8)	2.1 (5.4)
TAKEOFF – 2-SEGMENT APPROACH	11.0 (28.5)	5.2 (13.5)	7.3 (18.9)	2.7 (7.0)
TAKEOFF/CUTBACK – 2-SEGMENT APPROACH	4.6 (11.9)	3.0 (7.8)	3.6 (9.3)	2.1 (5.4)

RETROFIT AND ECONOMIC ANALYSIS

The market for DC-9 Refan retrofit airplanes was estimated at between 525 and 550 aircraft depending upon the date of noise abatement rule making During the early 1980's approximately 800 DC-9's are anticipated to be in service worldwide. The retrofit market amounts to approximately two-thirds of the total aircraft delivered. Of the 500 aircraft it was estimated that two-thirds would be retrofitted by domestic airlines.

The retrofit and economic analysis indicates that the estimated unit cost of the retrofit program is 1.338 million in mid-1975 dollars with about an equal split in cost between airframe and engine. This estimate has increased substantially from the 1972 levels and is almost solely the result of price inflation and the current lower aerospace industry operating levels.

Retrofitting a DC-9 airplane with the JT8D-109 engine modification could be accomplished in about 16-1/2 days after some experience has been accumulated. Figure 23 indicates that a domestic and foreign DC-9 Refan airplane retrofit program could be completed in early 1983 provided the Retrofit Program authority to proceed (ATP) occurs in mid-1976.

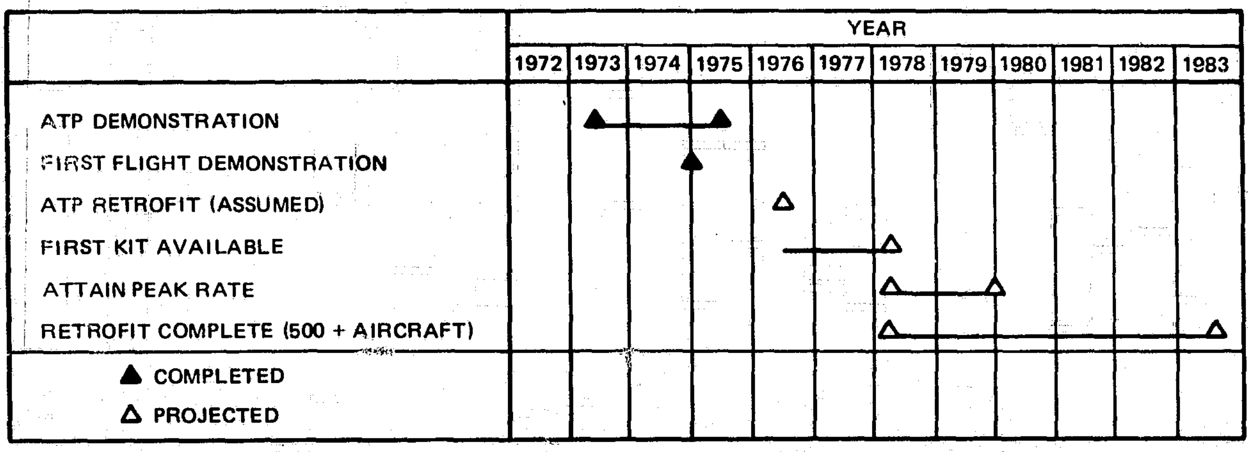


FIGURE 23. DC-9 REFAN RETROFIT SCHEDULE SUMMARY

SUMMARY OF RESULTS AND CONCLUSIONS

The purpose of the Refan Program was to determine the technical and economic feasibility of reducing airport community noise produced by JT8D powered airplanes through modifications to existing engines and nacelles. The Douglas Aircraft Company Phase II effort is summarized in this report.

New pylon and nacelle hardware were required for the JT8D-109 engine installation on the DC-9 airplane. Fuselage structural modifications were also necessary to handle the larger, heavier, and higher thrust engine installation.

The pylon width decreased from 425 mm (16.75 in.) to 204.5 mm (8.05 in.). The fuselage frames in the area of the pylon and the keel beams in the wheel well were strengthened by structural modifications and the fuselage titanium skin panels adjacent to the pylon were replaced with a heavier gauge.

The acoustic material used in the nose cowl was bonded aluminum honeycomb sandwich and the exhaust duct material was Inconel 625 Stresskin.

The installation of the JT8D-109 engine results in an operational weight increase of 1 041 kg (2,294 lb) and an aft operational empty weight center of gravity shift of 6 to 7 percent M.A.C. At sea level standard day conditions the additional thrust of the JT8D-109 results in 2 040 kg (4,500 lb) additional takeoff gross weight capability for a given field length.

The range change of the DC-9 Refan relative to the production DC-9 airplane for long range cruise at 10 668 m (35,000 ft) and payloads illustrating takeoff-gross-weight and fuel capacity limited cases are -352 km (-190 n.mi.) and -54 km (-29 n.mi.) respectively. Also, the range changes for 0.78 Mach number cruise at 9 144 m (30,000 ft) and payloads same as above are -326 km (-176 n.mi.) and -50 km (-27 n.mi.) respectively.

The DC-9 Refan airplane with the typical mission payload 6 804 kg (15,000 lb) and 694 km (375 n.mi.) range, shows less than 1 percent increase in block fuel for both the long range cruise at 10 668 m (35,000 ft) and 0.78 Mach number cruise at 9 144 m (30,000 ft) cases.

The Refan airplane demonstrated stall, static longitudinal stability, longitudinal control, longitudinal trim, air and ground minimum control speeds, and directional control characteristics similar to the production DC-9-30 and satisfied production airplane airworthiness requirements.

The climb performance of the DC-9 Refan airplane relative to the production DC-9-30 shows an 8 percent improvement in second segment and approach limiting weights and a 5 percent improvement in enroute limiting weight. The cruise performance data showed the range factor from 5 to 7 percent lower than an equivalent JT8D-9 powered DC-9-30 production airplane.

Thrust reverser performance was demonstrated at speeds below the operational cutback speed of 30.87 m/s (60 knots) with acceptable engine operation. The engine nacelle compartment ventilation, subsystem component, generator, and constant speed drive cooling systems were demonstrated satisfactorily for ground and inflight conditions. The nose cowl ice protection system flight evaluation shows that the system provides ice protection performance which is equal to or in excess of predictions.

The DC-9 Refan airplane structural and dynamic analytical results compared to ground and flight test data substantiate program requirements that the nacelle, thrust reverser, hardware, and the airplane structural modifications are flightworthy and certifiable and that the Refan airplane meet flutter speed margins.

The noise levels determined from the DC-9 Refan flyover noise tests conducted in compliance with Federal Aviation Regulations, Part 36 were 95.3 EPNdB for sideline, 96.2 EPNdB for takeoff, 87.5 EPNdB for takeoff with cutback, and 97.4 EPNdB for landing approach.

The noise reductions achieved by the DC-9 Refan airplane may be indicated by comparison with a baseline airplane equipped with JT8D-9 hardwall nacelles. Limited flyover-noise tests of a C-9A military version of the production DC-9 Series 30 indicated that the FAR Part 36 noise levels were 95.7 EPNdB for takeoff with cutback and 106.1 EPNdB for landing approach.

The DC-9 Refan flight test program provided extensive flyover noise data in a range of power settings and distances from the airplane to the microphones. Because of the completeness of the test data, the limits of the 90 percent confidence for all derived noise levels are within ± 0.8 EPNdB.

The retrofit and economic analysis indicate that the estimated unit cost of the retrofit program is 1.338 million in mid-1975 dollars with about an equal split in cost between airframe and engine.

REFERENCES

1. Anon.: "DC-9/JT8D Refan Phase I Final Report", MDC J5738, Douglas Aircraft Company, (NASA CR-121252), November 1973.

2. Anon.: "DC-9 Flight Demonstration Program with Refanned JT8D Engines, Final Report, Volume II, Design and Construction", MDC J4510, Douglas Aircraft Company, (NASA CR-134858), 1975.

3. Anon.: "DC-9 Flight Demonstration Program with Refanned JT8D Engines, Final Report, Volume III, Performance and Analysis", MDC J4519, Douglas Aircraft Company, (NASA CR-134859), 1975.

4. Anon.: "DC-9 Flight Demonstration Program with Refanned JT8D Engines, Final Report, Volume IV, Flyover Noise", MDC J4518, Douglas Aircraft Company, (NASA CR-134860), 1975.

5. Callaghan, J.T., Donelson, J.E., and Morelli, J.P., "The Effects on Cruise Drag of Installing Refan Engine Nacelles on the McDonnell Douglas DC-9", MDC J5948, Douglas Aircraft Company, (NASA CR-121219), 1973.

6. Chrisenberry, H.E., Doss, P.G., Kressly, A.E., Prichard, R.D., and Thorndike, C.S., "The Results of a Low Speed Wind Tunnel Test to Investigate the Effects of Installing Refan JT8D Engines on the McDonnell Douglas DC-9-30", MDC J5961, Douglas Aircraft Company, (NASA CR-121220), 1973.

SYMBOLS

dB(A)	A-weighted sound level, db
EPNdB	Unit of effective perceived noise level
EPNL	Effective perceived noise level, EPNdB
FAR	Federal Aviation Regulation
F_N	Uninstalled Net Thrust
F_{NC}	Installed Net Thrust
M	Flight Mach Number
M.A.C.	Mean Aerodynamic Chord
MCT	Maximum Continuous Thrust
M_o	Freestream Mach Number
MTOGW	Maximum Takeoff Gross Weight
MTW	Maximum Design Taxi Weight
OEW	Operational Empty Weight
SFC	Specific Fuel Consumption
TSFC	Thrust Specific Fuel Consumption
W/δ	Airplane Corrected Gross Weight
W_R	Airplane Gross Weight Ratio
X	Aircraft Inboard-Outboard Station
Y	Aircraft Fore-Aft Station
Z	Aircraft Vertical Station